Feasibility Study on Tidal Power Barrages

Including general plant design and site selection

Final report

Jerome van Harn 26 January 2007

Delta Marine Consultants bv

TU Delft Technische Universiteit Delft

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Preface

This master thesis is the result of a months-long study at Delta Marina Consultants (DMC). At the same time, the report is the final part of my study Civil Engineering at the Technical University Delft, with a specialisation in Coastal Engineering.

This report was not possible without the help of many people. I would like to thank my commission for their important contributions: Prof.dr.ir. M.J.F. Stive, ir. J. van Duivendijk, ir. H.J. Verhagen, dr. Ir. P.J. van Overloop and ir. E. ten Oever in particular.

In addition, I would like to thank Markus Muttray (DMC) for his support and Pierre Marin (Alstom Power France) for his contribution on turbines.

Jerome van Harn — Gouda, January 2007

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Nomenclature

a) Roman letters

A	= surface area, in square meters (m^2)
B	= unit cost of material, in dollars per cubic meter ($/$m^3$)
C	= construction cost, in dollars ($)
Ch	= Chézy coefficient, in square root meters meter second ($m^{1/2}/s$)
D	= diameter, in meters (m)
E	= energy production, in megawatt hour (MWh)
g	= gravitational acceleration, assumed to be a constant equal to 9.81 m/s^2
h	= head, in meters (m)
H	= height, in meters (m)
k	= dimensionless shaft losses, varying from 0 to 1 (-)
L	= length, in meters (m)
m	= dimensionless slope of barrage walls or shores (-)
N	= dimensionless parameter indicating a number (-)
N_{spec}	= specific speed, in revolutions per minute (rmp)
P	= generated power for a given site, in megawatt (MW)
Q	= discharge, in cubic meters per second (m^3/s)
r	= dimensionless ratio (-)
R	= mean tidal range (MHW-MLW) unless mentioned otherwise in subscript, in meters (m)
s	= distance, in meters (m)
t	= time, seconds (s)
T	= (tidal) period (for a semidiurnal tide; 12.42 hours = 44712 s), in seconds (s)
u	= flow velocity, in meters per second (m/s)
V	= volume, in cubic meters (m^3)
w	= width, in meters (m)
W	= energy volume, in megawatt hour (MWh)
wf	= dimensionless weight factor (-)

b) Greek letters and others

α	= dimensionless factor (-)
β	= dimensionless power output parameter (-)
Γ	= dimensionless flow parameter (-)
Δ	= dimensionless relative density (-)
η	= dimensionless efficiency parameter (-)
θ	= phase difference, in radians (rad)
κ	= dimensionless feasibility parameter (-)
λ	= dimensionless basin shape parameter (-)
π	= dimensionless ratio of a circle's circumference to its diameter, constant 3.141593
ρ	= water density, in kilograms per cubic meter (kg/m^3)
σ	= dimensionless Thoma's number (cavitation coefficient) (-)
ω	= $2\pi/T$, in 1 per meter (= frequency) ($1/T$)
ψ	= dimensionless Shields parameter (-)
$	= USdollars (USD)

Subscripts

*	= critical
0	= mean sea level
1	= first
2	= second
A	= surface area
a	= atmospheric
barrage	= barrage
bas	= basin
bed	= bed
bulb	= Bulb turbine

c	= construction
capacity	= capacity
closure	= closure
costs	= costs
costopt	= cost efficient optimum design point
d	= depth
dam	= dam
double	= double regulated
end	= end
excav	= excavation
g	= generator
generation	= generation
grid	= grid (distance)
high	= high
HWS	= high water springs
in	= normal flow direction
l	= length
life	= life time
low	= low
LWS	= low water springs
construction	= construction
max	= maximum, in case of tidal range: HHWS-LLWS
maxopt	= maximum output optimum design point
mc	= mass centre
mean	= mean
MHW	= mean high water
MHWS	= mean high water springs
min	= minimum
MLWS	= mean low water springs
netto	= netto
one	= One-way generation
open	= open
out	= reverse flow direction
p	= powerhouse
part	= particle
pot	= potential
pump	= pump
rated	= rated
rect	= rectangular shape
req	= required
s	= sluice gates
scheme	= generation scheme
sea	= sea / water outside basin
sign	= significant
single	= single regulated
stability	= stability requirement
start	= start
stop	= stop
stormsurge	= stormsurge
straflo	= Straflo turbine
suct	= suction
T	= tidal period
t	= total
tidal	= tidal
trans	= transmission
turbine	= turbine
two	= Two-way generation
v	= vapour
w	= water
wave	= wave

Abstract

Tidal power is a proven technology to produce electricity and has the potential to generate significant amounts of electricity at certain sites around the world. However, only limited guidance is available for a cost efficient tidal power plant design and the selection of a suitable site. Both items are addressed in this study, together with a comparison of the tidal power costs to the costs of other (renewable) energy sources.

Within this study the possible concepts for tidal barrages have been analysed, from which a single basin layout showed to be the most attractive plant layout. This layout could be combined with three generation modes; One-way generation, Two-way generation and generation with additional pumping.

For these concepts, a general plant design has been analyzed, to determine the general dimension of the essential plant components, including; powerhouse, sluice gates, barrage dam, bed protection and transmission lines. Aspects like cavitation and required excavation are taken into account.
The construction costs for these components are mainly estimated by multiplying the defined volume of material by the unit costs.

As the turbines and further electromechanical equipment required further detailed study, this is studied separately from the general plant design.
From this, a turbine diameter of 5-8 m is suggested for all sites and a method is introduced to determine the optimum number of turbines and sluice gates. By studying the efficiencies and costs, for One-way generation the single regulated Bulb turbine was proven to be the most attractive turbine type. For Two-way generation the double regulated Bulb turbine is suggested. This study showed that Two-way generation is the most attractive generation mode, as is has at least a 19% higher power output over a tidal period than One-way generation.
With the use of the Dynamic Tidal Power Model the optimum plant capacity is defined together, with the required head difference for generating.
As little was known about the effect of pumping at tidal power barrages, this has been worked out. Pumping water out or into the basin is shown to be not profitable at constant electricity costs over a day as it consumes more power than it produces, but gains potential when electricity rates are lower (i.e. at night).
The essential plant design parameters which require optimization are taken into account in the Generic Plant Design Guideline, which describes the required procedures to come to their optimum values.

After the general tidal power plant and turbine design were defined, the site selection process could be worked out. The essential parameters resulting in a valuable site selection were determined. With this, a method was introduced to define the attractiveness of a site. A site that does not meet the required mean tidal range criterion of 7 m, can not reach the most economic design for tidal power barrages and will lose attractiveness. With other types of turbine different from the common applied turbines, lower mean tidal ranges could be sufficient.
This process resulted in the Generic Site Selection Guideline, which includes technical aspects as well as economical aspects of a specific site.

To define the economical position of tidal power in relation to other electricity sources, the costs of tidal power were determined. This included the investment costs as well as the operational and maintenance costs during its life time.
Compared to the other electricity sources, tidal power showed to have high investment costs and low operational and maintenance costs. From this it can be concluded that tidal power has the potential to compete with other electricity sources.

One of the most important recommendations which can be made on the basis of this study is further research in the possible environmental aspects of tidal power barrages regarding morphology, water level changes and impact on fish habitats. In addition, this thesis shows that tidal power in combination with energy storage is possible, but should be further elaborated as this could increase the total feasibility.

Chapter 1 Problem Analysis

1.1 Introduction

Renewable energy is at the moment a widely discussed subject, which is mainly caused by its environmental benefit, namely the reduction of CO_2, and by its inexhaustible supply benefit compared to conventional energy sources (European Commission, 1997). These advantages are the main reasons for the increase of renewable energy demand.
According to the Kyoto protocol, the European Union has committed itself to a greenhouse gas (GHG) reduction of 8 percent within the European Union by the years 2008-2012, as compared to 1990. Renewable energy sources are expected to play an important role in the implementation of these GHG-targets. In its White Paper (European Commission, 1997), a strategy for the development of renewable energy, the European Commission has set up a goal of supplying 12 percent of the European Union's energy consumption by the year 2010 (twice the 6 percent level in 1997) from renewable energy sources. Within these total energy targets, the generation of electricity is a key factor (European Wind Energy Association, 2005).

The International Energy Agency (IEA) predicts that next to the European market, the market for renewable energy in the United States will also project an increase in supply, however somewhat less.
According to the European Commission the increasing demand and supply of renewable energy has a positive effect on the cost price:
"Current trends show that considerable technological progress related to renewable energy technologies has been achieved over recent years. Costs are rapidly dropping and many renewables, under the right conditions, have reached or are approaching economic viability." (European Commission, 1997).

The environmental benefits and infinite stock, the increasing interest and demand and its economic feasibility potential are enough reasons to look for renewable energy alternatives.

Such an alternative could be found in the ocean by using the tides, which already has been used for the production of energy around the 9th century in Iraq. The earliest document detected on tidal power dates back to 1917[1], but tidal power has really drawn the attention since the first tidal power plant has been in operation (La Rance, 1966) with conferences, literature, feasibility studies and new tidal power projects.
According to the United Nations Division for Ocean Affairs and the Law of the Sea (UN-DOALOS):
"Tidal power is a proven technology and has the potential to generate significant amounts of electricity at certain sites around the world. Although, our entire electricity needs could never be met by tidal power alone, it can be an invaluable source of renewable energy. The negative environmental impacts of tidal barrages are probably smaller than those of other sources of electricity, but are not well understood at this time. The technological feasibility of both major and minor tidal power designs has been established and the main barrier to increased use of the tides is that of construction costs. The future costs of other sources of electricity, and concern over environmental impacts, will ultimately determine the exploitation of tidal power."(United Nations Divisions for the Ocean Affairs and the Law of the Sea, 2001)

This reflects the existing doubts about the feasibility of tidal power, where the conclusion of the UN-DOALOS is taken as an example here.

[1] Ringers, J.A. 1917: Beschrijving van den bouw van de derde schutsluis in het kanaal door Zuid-Beveland te Hansweert

1.2 Problem definition

Because of the doubts about the feasibility of tidal power, a reasonable amount of investigations and feasibility studies for tidal power projects have been undertaken. Examples are the feasibility studies on the Severn and Mersey Barrages in the UK (Institution of Civil Engineers, 1982), the Derby Barrage in Australia (Hydro Tasmania, 2001) and the possibilities for the Bay of Fundy in Canada (Conference Board of Canada, 2003).

Tidal power can be generated by using tidal currents (underwater mills) or water level differences (barrages). In this study the focus will be on the latter option; the transformation of water level difference into electrical energy with tidal power barrages.
To the author's knowledge only eight tidal power plants have been built so far. However, only the tidal power plants of La Rance in France and Sihwa in South Korea can be considered as prototype. The others are in fact pilot plants.

The site as well as the tidal power plant design has to meet various criteria. However, only limited guidance is available for a cost efficient tidal power plant design and the selection of a suitable site. Both items will be addressed in this study.

1.3 Study objectives and study approach

This study investigates the technical feasibility of tidal power generation. A guideline will be drawn up for a cost efficient tidal power plant design and site selection, clarifying which aspects are critical for a potential tidal power plant design and site. This makes it possible to compare the costs of tidal energy to the costs of other (renewable) energy sources.
The objectives of the study are:

- To draw up a generic guideline for tidal power plant design
- To draw up a generic guideline for site selection
- To determine the costs of tidal energy

The methodology of the study is rather an iterative process than stepwise approach, which is illustrated by Figure 1.1.

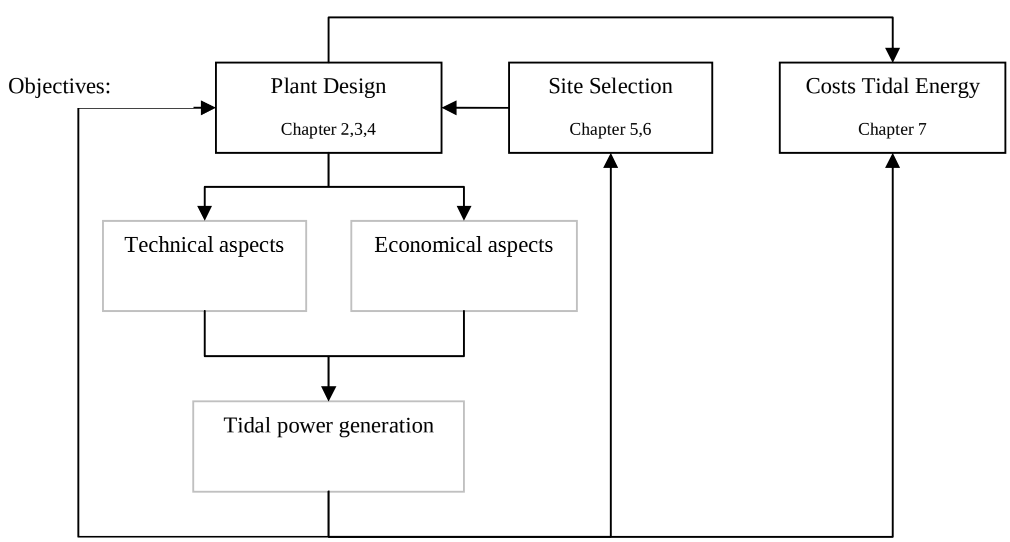


Figure 1.1 Study approach

Draw up a generic guideline for tidal power plant design
The technical feasibility for the different barrier plant designs, considering the different concept options, will be determined and evaluated. The different plant components will have to be discussed, with the turbine design in specific. The guideline should contain the required procedures to derive the essential plant design parameters which require optimization. These parameters will be investigated with the help of the Dynamic Tidal Power Model.

Draw up a generic guideline for site selection
The technical feasibility criteria for tidal power sites will be determined and evaluated giving a proper view on the different aspects concerning this investigation. The guideline should contain technical aspects as well as economical aspects.

Determine the costs of tidal energy
At the end of this study the costs for tidal energy generation will be compared to other energy sources. For this, the construction costs will have to be determined as well as the operational and maintenance costs.

Chapter 2 Plant concepts

To come to the final Generic Plant Design Guideline, first the different tidal power barrage concepts will have to be introduced. A plant concept is characterized by the plant layout and the generation mode, which is illustrated in Figure 2.1.

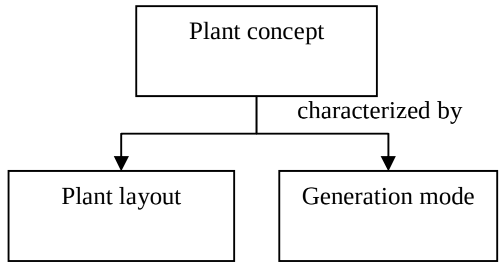


Figure 2.1 Relation plant concept with layout and generation mode

The objectives and approach of this chapter will be as follows:

Objective:
- **Determine the most promising plant concept**

Approach:
- **Investigate the possible plant layouts and their characteristics**
- **Investigate the possible generation modes and their characteristics**

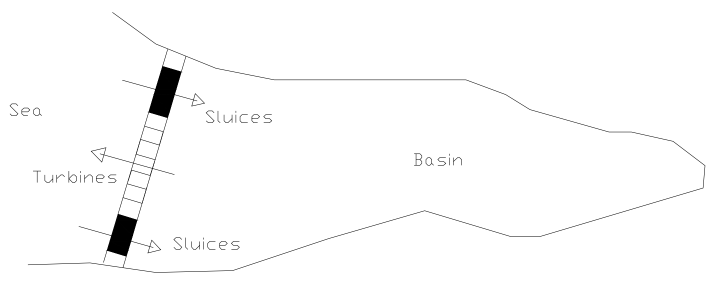
This chapter will start with describing the possible plant layouts in 2.1, while section 2.2 discusses the generation modes. Finally, in section 2.3 the most promising plant layout(s) and generation mode(s) will be selected and applied for further study.

2.1 Plant layouts

Three possible plant layouts can be considered:
- Single basin (subsection 2.1.1)
- Multiple basins (subsection 2.1.2)
- Basin combined with energy storage

The single basin layout is the most common implemented (in operational tidal power plants and tidal power feasibility studies) and uncomplicated layout option. A multiple basins layout requires, as the name indicates, multiple basins. Combining a tidal power plant with a type of energy storage has been studied. This combination showed indeed to be feasible (see subsection 5.3.2), but will not taken into account for simplicity purposes.

2.1.1 Single basin



A typical single basin layout is shown in the Figure 2.2, characterized by a basin separated from sea by one barrage structure The tidal basin will be filled during the rising tide through the sluice gates. At falling tide the sluice gates will be closed and water will pass the turbine, generating electricity.

Figure 2.2 Single basin layout (for One-way generation)

A typical schematisation of the water levels, heads and operation processes can be seen in Figure 2.3. **Main advantages are the simplicity of construction and operation and the relative high power output due to the fact that large head difference can be created.**

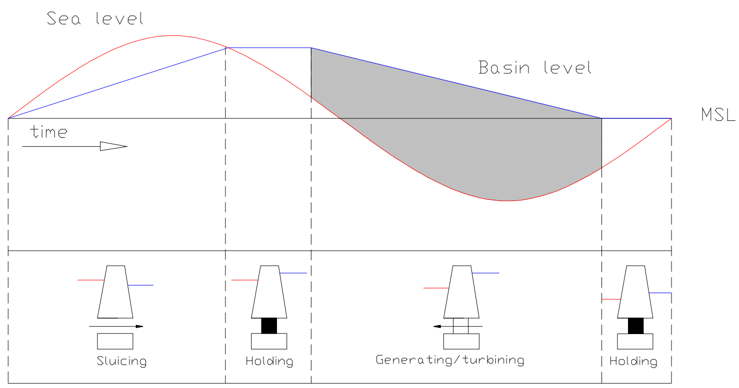


Figure 2.3 Schematisation of water levels and operational processes for a single basin layout (One-way ebb generation)

2.1.2 Multiple basins

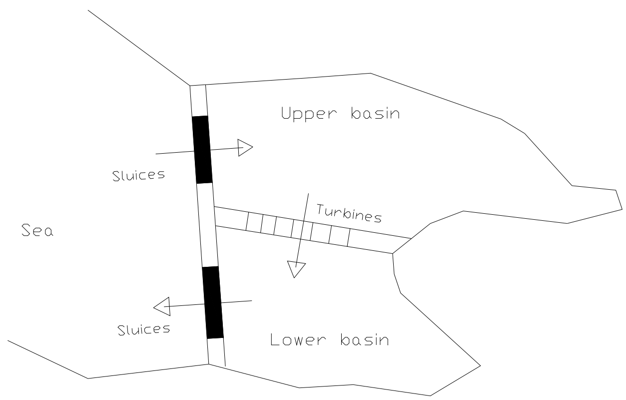


Figure 2.4 Multiple basins layout

Tidal energy has the large disadvantage that the energy production is a very discontinuous process where supply does not meet with the load. To reduce this effect, a multiple basins tidal power scheme is introduced shown in Figure 2.4. Instead of using just one basin, multiple basins (two in this example) are applied. The sluice gates are placed in the outer barrage while the turbines connect the inner basins (upper and lower).

As illustrated in Figure 2.5 this method produces energy continuously.

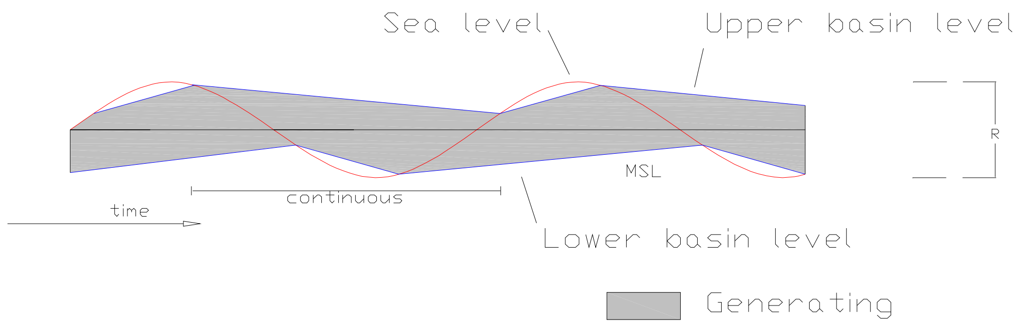


Figure 2.5 Possible multiple basins generation scheme

But, this advantage does not compensate the disadvantages. The extra barrage length separating the inner basins increases the project costs, but most important; **the total energy production is only 50% of the production for single basin One-way generation and even less compared with single basin Two-way generation** (Duivendijk, 2004). These two types of generation, the generation modes, will be discussed in the next section.
This power output level was to be expected, as the turbine requires a continuous minimum head difference *h* over the turbines, resulting in a low number of turbines and thus (mean) power output. This prevents the upper basin water level from lowering too rapidly and the lower basin level from rising too rapidly. That is exactly why the slopes of the schemed basin levels are so gentle. For further explanation about multiple basins operation, see (Duivendijk, 2004).

Besides the low mean power output, less site locations will have attractive geographical (shape) characteristics for multiple basins application compared to single basin generation.
This makes the multiple basins layout less interesting as tidal layout option.

2.2 Generation modes

A generation mode, also called mode of operation, describes the method for power generation. It is common to describe generation modes by generation schemes; a scheme showing the water level outside (sea) and the water level inside (basin). Each generation mode has its own scheme, thus characteristics.
Combining these scheme characteristics with some power equations makes it possible to derive the (mean) power output per generation mode. This will be worked out later on in the report, but illustrates the essence of these generation schemes.

At the start of this study, the schemes were determined by characteristics from operational plants and feasibility studies (see Appendix B1), but with the use of the DTP Model a more cost efficient generation scheme could be generated (see Appendix A5). As the latter schemes are based on own research and a cost efficient scheme will increase the feasibility of a tidal power plant, these schemes will be used as the general generation schemes describing the modes of generation.

The following generation modes exist:

- One-way generation (subsection 2.2.1)
- Two-way generation (subsection 2.2.2)
- Generation with additional pumping (subsection 2.2.3)

2.2.1 One-way generation

One-way generation can be executed in two ways, by:

- Ebb generating (when basin level > sea level)
- Flood generating (when basin level < sea level)

For One-way generation, water passes the turbines only in one direction during generation and thus require sluice gates for the other direction.

Because of the high basin levels for ebb generation, shipping can be permitted, which is a large advantage compared to flood generation.

The resulting generation schemes are illustrated in Figure 2.6 and 2.7, with the sea level in red and basin level in blue.

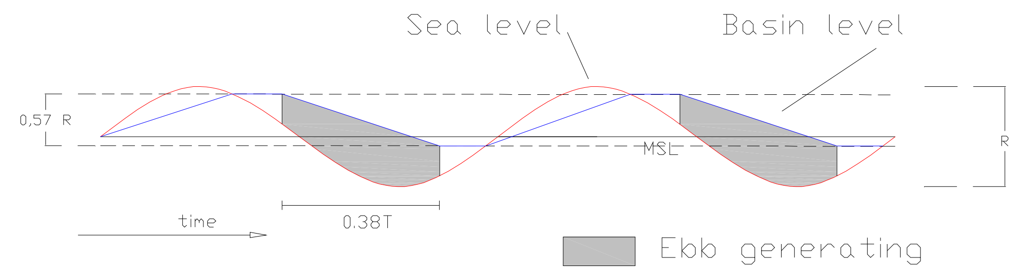


Figure 2.6 General One-way ebb generation scheme

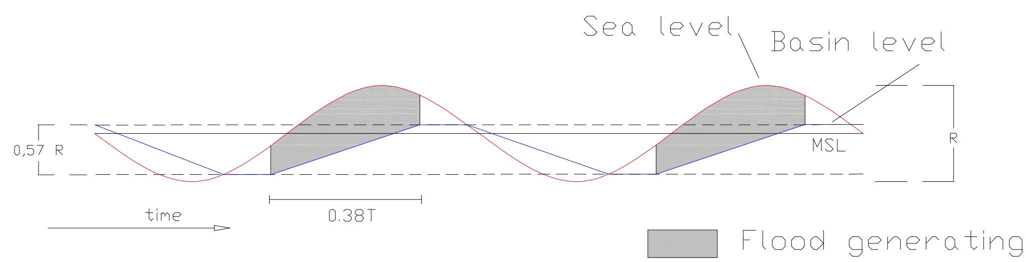


Figure 2.7 General One-way flood generation scheme

The grey surfaces in the generation schemes are often misunderstood by presuming it to be similar as the energy output. But, as will be shown by in subsection 4.2.4, the power has to be a function of $h^{3/2}$ and thus energy (power time generation period) follows $h^{3/2}*T_{generation}$ and not $h*T_{generation}$. The grey surface just indicates in what section of the scheme energy will be generated.

2.2.2 Two-way generation

With Two-way generation, turbines generate in two directions. This means that no sluice gates are required for power generation. Nevertheless, further study will show the positive effect of sluice gate for the power production. Their effect on the generation scheme is visual in Figure 2.8, just after the generation period, where basin level raises and lowers more rapidly.

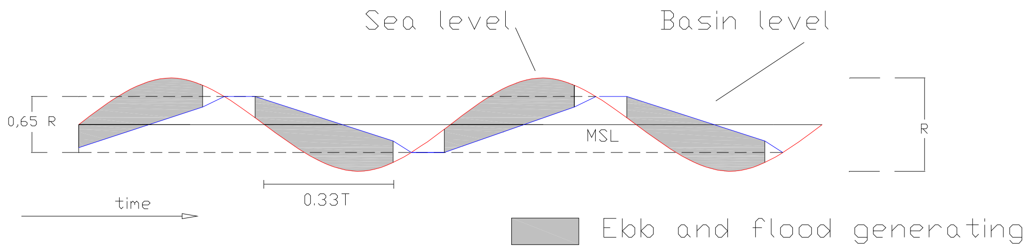


Figure 2.8 General Two-way generation scheme

The generation mode properties from the three generation schemes are listed in the following table:

Table 2.1 Properties for different generation modes (see Appendix A5)

	One-way ebb generation	One-way flood generation	Two-way generation
h_{req}	0.28R	"	0.28R
h_{mean}	0.46R	"	0.39R
h_{max}	0.56R	"	0.46R
R_{bas}	0.57R	"	0.65R
$T_{generation}$	0.38T	"	0.33T
$H_{w,bas,high}$	0.44R	0.13R	0.37R
$H_{w,bas,low}$	-0.13R	-0.44R	-0.28R
$H_{w,bas,mean}$	0.15R	-0.15R	0.04R

Where:
h_{req} = required head over turbines for generation, in meters (m)
h_{mean} = mean head over turbines during generation, in meters (m)
h_{max} = maximum head over turbines during generation, in meters (m)
R_{bas} = basin range, in meters (m)
$T_{generation}$ = generation period, seconds (s)
$H_{w,bas,high}$ = high basin level referred to MSL, in meters (m)
$H_{w,bas,low}$ = low basin level referred to MSL, in meters (m)
$H_{w,bas,mean}$ = mean basin level referred to MSL, in meters (m)

2.2.3 Additional pumping

In addition to the One-way or Two-way modes of generation, it is also possible to adjust water levels by using pump turbines. These are turbines which could function as pumps, enable to raise the higher basin levels and to drop the lower basin levels enlarging the head differences in the basin. With pumping, instead of generating power from the turbines, the turbines consume power so that afterwards a higher power output can be generated.
The Figures 2.9 and 2.10 illustrate a One-way and Two-way generation scheme with additional pumping.

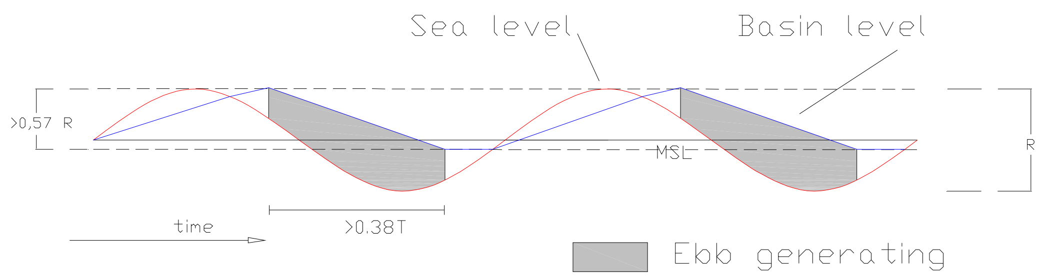


Figure 2.9 Possible One-way generation scheme with additional pumping

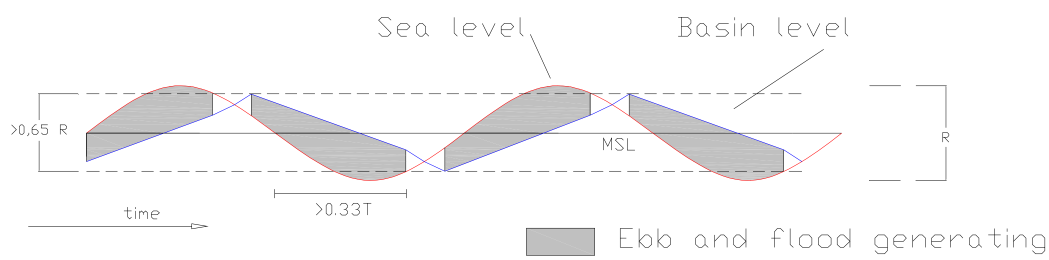


Figure 2.10 Possible Two-way generation scheme with additional pumping

The figures clearly show that for One-way generation the basin level only will be forced to raise or drop in one direction, while for the Two-way generation scheme pumping will be commonly implemented in both directions (compare Figure 2.9 with 2.6 and 2.10 with 2.8).

At the moment, La Rance is the only operational tidal power plant using turbines as pumps. Here fore, special turbines were constructed; pump turbines.
Pump turbines can be seen as double regulated turbines with a slight difference in runner blade shape, resulting in higher efficiencies during pumping. On the other hand, this also reduced the efficiency level during turbining (see subsection 4.2.2).
As Two-way generation plants already require double regulated turbines with adjustable runner blades and guide vanes, they almost already are in the possession of pump turbines. This is not the case for a One-way generation plants where less adjustable turbines are also possible and reduces the turbine cost. In fact, this means that in case of Two-way generation pumping will have less influence on the turbine design and thus on the costs than for One-way generation.
For that reason pumping can be expected to be more profitable for a Two-way generation scheme than for a One-way generation scheme. Therefore, it is not a surprise that La Rance is a Two-way generation plant.

2.3 Conclusions

For further study, only the single basin layout will be considered, multiple basin was less attractive and a combination with a type of energy storage is outside the scope of this study.
This layout can be combined with three generation modes, where the attractiveness of addition pumping will be an important aspect for further study. Unless the fact that pumping, if profitable, will only expect to be economic attractive for Two-way generation, also pumping in a One-way generation scheme will have to be investigated to compare the mean power output.
This means the following three plant concepts will be worked out consequently:

- Single basin – One-way generation
- Single basin – Two-way generation
- Single basin – Generation with additional pumping (One-way and Two-way generation)

The general plant design for these concepts can be found in the next chapter.

Chapter 3 General plant design

A tidal power plant consists of the following civil works:

- Powerhouse
- Sluice gates
- Barrage dam
- Bed protection
- Transmission lines

The turbine design will be discussed separately in the next chapter.

As, later on, the construction costs will mainly be estimated by multiplying the defined volume *V* of material multiplied by the unit costs *B* ($/m^3), the total material volume specified by civil work will be mentioned.

Objective:

- **Define a general plant design**

Approach:

- **Analyse existing methods to assess general plant dimensions**
- **Formulate new methods to assess general plant dimensions**
- **Select preferred method and define site specific parameters**

This chapter will describe the general dimensions of the different civil works, related to the site specific parameters: powerhouse in 3.1, sluice gates in 3.2, barrage dam in 3.3, bed protection in 3.4 and the transmission lines in 3.5. Section 3.6 will list the resulting plant design parameters.

3.1 Powerhouse

The powerhouse is another name for the turbine caisson, in where the turbines and generator will be placed. In general, one turbine caisson contains two turbines.

3.1.1 Existing method

Fay and Smachlo derived the following empirical[2] formula for the general powerhouse volume V_p per turbine caisson (Fay and Smachlo, 1983-I):

$$V_p = 42 \cdot R \cdot D_{turbine}{}^2 \quad (\mathrm{m}^3) \tag{3-1}$$

Where,
V_p = powerhouse volume according to existing method, in cubic meters (m^3)
$D_{turbine}$ = turbine diameter, in meters (m)

Here, no theoretical background could be given for the empirical generated value 42. For this reason, a new method will be presented, which will be used for further study.

[2] Based on representative values from Cobscook, Fundy and La Rance tidal power projects

3.1.2 New method

This method will also be based on determining the powerhouse volume V_p, by multiplying length L and width W and height H. Here, the length is defined by the distance along the barrage and the width by the distance across the dam (see figure).

The space requirement of a powerhouse varies with the turbine type (Raabe, 1985). Taken into account are the two most applied types of turbine for tidal power plant studies; the Straflo turbine and the Bulb turbine. These turbines will be worked out in section 4.1.

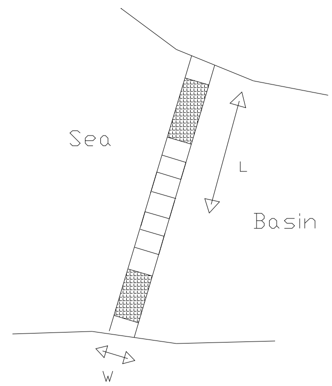


Figure 3.1 Definition length and width

The powerhouse volumes, $V_{p,straflo}$ for the Straflo turbine and $V_{p,bulb}$ for the Bulb turbine, can be determined by predicting their height, length and width. For simplicity purposes, one turbine per powerhouse was considered, which will not affect the plant design.

Length and width are easy to derive with some simplification made by (Raabe, 1985). The height on the other hand will depend on a list of parameters:

- Highest water level outside
- Wave climate
- Excavation depth

For this study however the extra construction stability height, to provide extra weight to assure the stability of the construction, will assumed to be zero.

Highest water level outside

The construction height will largely depend on the highest water level outside the barrage, which will be derived from the water level at MHWS plus the storm surge $H_{stormsurge}$. The highest water level outside can thus be written according to: $H_{w,mean} + ½R_{max} + H_{stormsurge}$.

Wave climate

The local wave climate, including aspects as wave run-up and overtopping, should be added to the water level. The powerhouse will then be constructed as high as the top level of the *barrage dam, which is assumed to be a rubble mound*. For this (permeable) type of dam a save overtopping scenario will consist of a wave run-up equal to two times the significant wave height. This will cause little hindrance to (possible) infrastructure on the dam (d'Angremond and van Roode, 2001).
This makes it possible to write the wave climate as follows: $2*H_{wave,sign}$.
Of course, wave climate remains an important site specific parameter, which means this simplification can only be used for a first rough estimation.

Excavation depth

Next to the previous described aspects related to water levels, the construction height will also have to take into account a certain excavation depth of the construction H_{excav}. When the site has not sufficient space (height) for the turbines, regarding the lowest tail water level, excavation will be necessary. For the most common modes of generation (Two-way generation and One-way ebb generation) the tail water level will be the lowest sea water level $H_{sea,MLWS}$.
The excavation depth can be written according to: $H_{excav} = H_{sea,MLWS} - H_{turbine} - H_{cav}$.
(Where, H_{excav} = excavation depth and H_{cav} = additional submergence due to cavitation)
The typical turbine height and the required cavitation height will be elaborated below.

The construction height consists of the turbine height, which is larger than the turbine diameter itself. The required turbine height can be derived from turbine space requirement determined by Raabe (1995), which are illustrated by Figure 3.2. Here on the left the space requirements for the Straflo turbine (type 1) are shown. On the right hand side the requirements for the Bulb turbine (type 2):

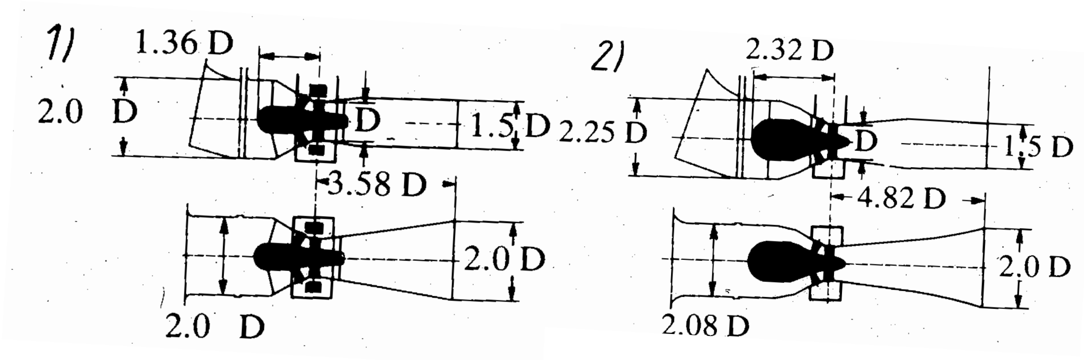


Figure 3.2 Space requirements for Straflo (1) and Bulb (2) turbine (Raabe, 1985)

Only the straight flow variant was taken into account, which means only the lower pictures of the figure.
The turbine shaft height was increased by an assumed 0.2*D* for the concrete layer around the turbine shaft. This results in the following turbine heights:

$$H_{turbine,bulb} = 2.3 \cdot D_{turbine} \quad \text{(m)} \tag{3-2}$$

$$H_{turbine,straflo} = 2.2 \cdot D_{turbine} \quad \text{(m)} \tag{3-3}$$

The length of the turbine shaft was taken (by measure) from Figure 3.2. The width is equal to the height of the shaft as the turbine front has a square surface. This information will be implemented further on.

Excavation could also be necessary when a turbine should be placed low under the minimum tail water level to avoid cavitation in the turbine.
Cavitation will take place when local pressure falls below the vapour pressure. It has negative influence on the turbine efficiency and could even cause severe damage to the turbine runner.

Cavitation can be avoided when the turbines are sufficiently submerged regarding the backwater level.
The dimensionless cavitation coefficient σ, also known as Thoma's number, is defined in terms of water pressure and atmospheric and vapour pressure heads:

$$\sigma = \frac{h_a - h_v - h_{suct}}{h} \quad (-) \tag{3-4}$$

Where,
σ = dimensionless Thoma's number (cavitation coefficient)
h_a = atmospheric pressure head (over turbines), in meters (m)
h_v = vapour pressure head (over turbines), in meters (m)
h_{suct} = suction head (over turbines), in meters (m)
h = head (over turbines), in meters (m)

The critical cavitation coefficient σ_* is defined as the maximum σ above which cavitation is likely to occur. The maximum suction head from the turbine axis, and thus the turbine setting, can be found by:

$$h_{suct} = h_a - h_v - \sigma_* \cdot h \quad \text{(m)} \tag{3-5}$$

At a tidal power plant the atmospheric pressure h_a will be the same as at sea level:

$$h_a = 10.3 \quad \text{(mwc)} \tag{3-6}$$

Sea water of 10^{o}C the vapour pressure h_v is:

$$h_v = 0.12 \quad \text{(mwc)} \tag{3-7}$$

According to Mainardis, the critical cavitation coefficient can be derived by the following formula, where the specific speed N_{spec} plays an important role (Mosonyi, 1963):

$$\sigma_* = 3 \cdot 10^{-6} \cdot N_{spec}{}^2 - 0.0008 \cdot N_{spec} + 0.1633 \quad (-) \tag{3-8}$$

For Bulb turbines the specific speed N_{spec} is (Ferc, 1991):

$$N_{spec} = \frac{1520.26}{h^{0.2837}} \quad \text{(rpm)} \tag{3-9}$$

The same specific speed will be assumed for the Straflo turbine.

As the required head difference will be 2 m (see section 5.6) and the maximum head difference will be approximately 10 m, it is possible to plot h_{suct} as function of h.
As head difference varies with the generation mode this should be conversed to the tidal range. In subsection 4.2.4 the maximum head, called rated head, at which turbines still generate will be introduced. The conclusions however, are required as cavitation criteria. Subsection 4.2.4 will show a maximum rated head for the most cost efficient plant design of 0.52*R* for One-way generation. With this, Figure 3.3 can be drawn.

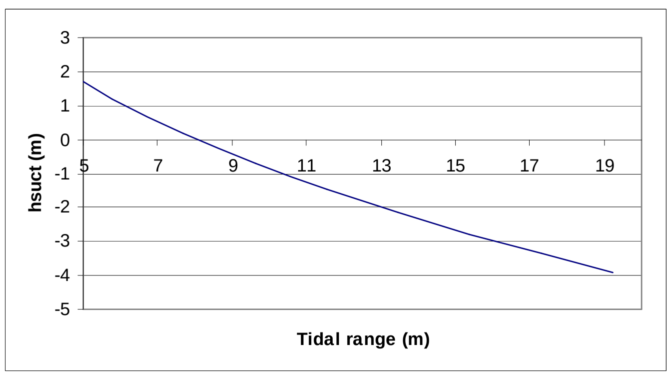


Figure 3.3 Maximum altitude turbine axis above lowest tail water level as function of the tidal range

The figure illustrates that submergence due to cavitation is required from a tidal range of about 8 m. As will be determined in subsection 4.2.3, a minimum turbine diameter of 5 m is suggested. This means that at least a h_{suct} of 5.5 m is present (with $H_{turbine}$ = 2.2*$D_{turbine}$). According to the figure, submergence due to cavitation can be neglected for turbines with a diameter larger than 5 m.

Note that, in case of turbine diameter less than 2,5 m [3] cavitation can affect the position of the turbines and the powerhouse height for extreme mean tidal ranges.

For this study, the storm surge will be neglected, which will be acceptable in combination with the conservative overtopping criteria.

[3] Assuming the largest R=14 m (-> h_{suct} =2.5m), 0.5*$H_{turbine}$ = 1.1*$D_{turbine}$, than $D_{turbine}$ = 2.3 m

The powerhouse construction height H_p can be calculated for two scenarios; with or without required excavation, see figures below.

Scenario with required excavation

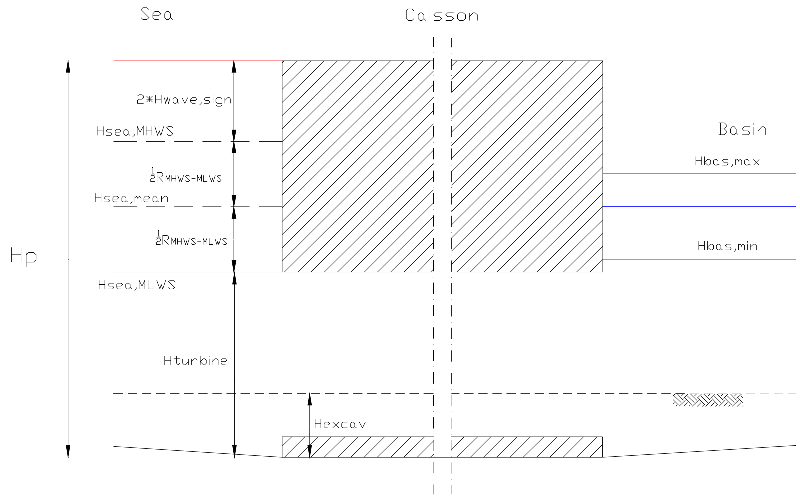


Figure 3.4 Construction height build-up with excavation required

Scenario without excavation

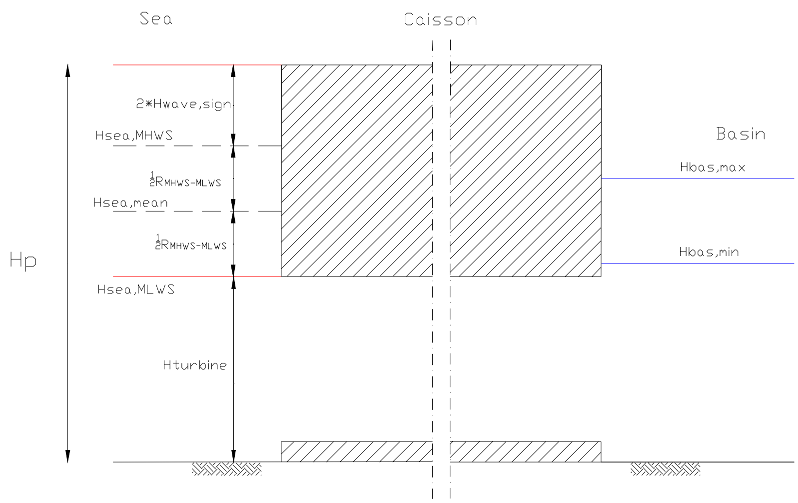


Figure 3.5 Construction height build-up without excavation required

For both scenarios the powerhouse height can be calculated by:

$$H_p = R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + H_{turbine} \quad \text{(m)} \qquad (3\text{-}10)$$

Where,
$H_{bas,min}$ = minimum basin height, in meters (m)
H_0 = basin height at MSL, in meters (m)
$H_{wave,sign}$ = significant wave height, in meters (m)

Now the construction heights H_p for the Bulb and Straflo turbine are derived, their volumes can be elaborated (Raabe, 1985). Because the volume is a function of the length, height and width of the powerhouse, these will be presented separately.

Bulb turbine:

$$W_{p,bulb} = 8.8 \cdot D_{turbine} \quad \text{(m)}$$

$$H_p = R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + H_{turbine} \quad \text{(m)}$$

$$L_{p,bulb} = N_{turbine} \cdot 2.3 \cdot D_{turbine} \quad \text{(m)}$$

$$V_{p,bulb} = N_{turbine} \cdot 20.2 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.3 \cdot D_{turbine}) \quad \text{(m}^3\text{)} \qquad (3\text{-}11)$$

Where;
$N_{turbine}$ = number of turbines (-)

Straflo turbine:

$$W_{p,straflo} = 6.6 \cdot D_{turbine} \quad \text{(m)}$$

$$L_{p,straflo} = N_{turbine} \cdot 2.2 \cdot D_{turbine} \quad \text{(m)}$$

$$V_{p,straflo} = N_{turbine} \cdot 14.5 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.2 \cdot D_{turbine}) \quad \text{(m}^3\text{)} \qquad (3\text{-}12)$$

The formulas above clearly show the difference in space requirement between the two turbine types, where the powerhouse for the Bulb turbine is about 40% larger than the Straflo turbine.

3.2 Sluice gates

Sluice gates indicate the caissons in where the sluice gates will be placed.

3.2.1 Existing method

The sluice gate volume V_s can be denoted by the following formula (Fay and Smachlo, 1983-I):

$$V_s = 18 \cdot R \cdot A_s \quad \text{(m}^3\text{)} \qquad (3\text{-}13)$$

Where,
A_s = sluice gate surface area, in square meters (m^2)

For the same reason as for the powerhouse volume (lack of theoretical background), a new model will be generated and used for further study.

3.2.2 New method

Sluice gates can be used:

- To refill of empty the basin after generation (One-way generation)
- To raise or lower the basin level more rapidly than under gravity flow (Two-way generation)

The choice of the installed sluice gate type will not be further worked out in this study. Whether the choice will fall on a sluice gate under free surface flow or a form of submerged sluice gates will be assigned to the constructor. Within this study the total sluice gate surface area remains constant during operation.

Appendix B4 shows that for present tidal power plants and feasibility studies the following relation exists between the total sluice gate surface area and the total turbine surface area:

$$A_{t,s} \approx 2 \cdot A_{t,turbine} \quad (\mathrm{m}^2) \qquad (B\text{-}9) \quad (3\text{-}14)$$

With the help of the DTP Model no valuable conclusions could be drawn with respect to the total sluice gate surface area, see Appendix A4. Therefore, the existing relation in formula 3-14 will be used for further study.

From the DTP Model results it can be stated that:

- **For One-way generation; no sluices means no power.**
- **Applying sluice gates for Two-way generation easily increases the mean power output with 10% each tidal period, which makes sluice gates alsovery attractive.**

The effect of sluices gates for Two-way generation is illustrated in the figure below. When opening the sluice gates at the end of the turbine period, the basin range will increase. This has a positive effect on the head difference and generation period.

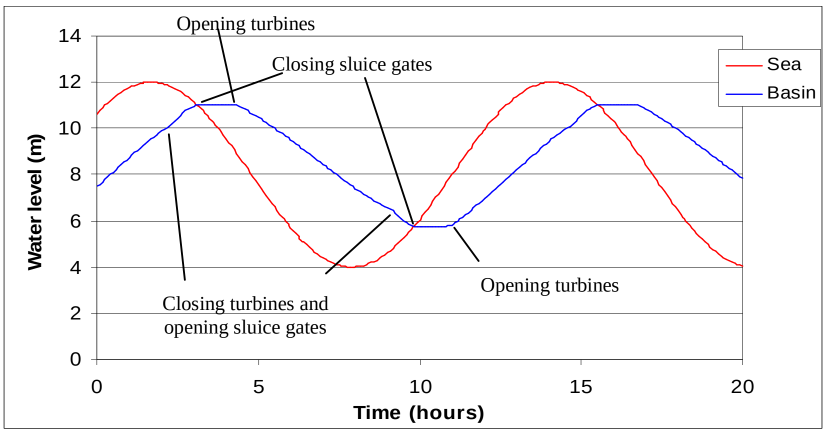


Figure 3.6 Positive effect of sluice gates on basin levels

The top of the sluice caissons are at the same level as the top of the powerhouse. However, no excavation due to low tail water level will be required for sluicing.
With reference to a study on the Severn tidal power plant, the width of a turbine caisson is about 1.5 times the width of a sluice caisson (Institution of Civil Engineers, 1982). The powerhouse width will be averaged over the turbine type, to avoid its influence on the sluice gate design.

Note that the opening surface of the sluice gates was shown to be about twice the opening surface of the turbines, *but because sluice gate openings can be placed closer to each other, the total sluice gate length will be assumed to be equal to the total turbine length*. This was also found in present feasibility studies for specific sites. Also the total sluice gate length will be averaged over the two turbine types.

From now on the height of the sluice gates and barrage dam, as they will be similar, will be named construction height H_c.

$$W_s = \frac{7.7 \cdot D_{turbine}}{1.5} = 5.1 \cdot D_{turbine} \quad \text{(m)}$$

$$H_s = H_c = H_0 + 0.5 \cdot R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} \quad \text{(m)}$$

$$L_s = N_{turbine} \cdot 2.25 \cdot D_{turbine} \quad \text{(m)}$$

$$V_s = N_{turbine} \cdot 11.5 \cdot D_{turbine}{}^2 \cdot H_c \quad (\text{m}^3) \qquad (3\text{-}15)$$

Where,
7.7 = average of both turbine types; (8.8+6.6)/2
2.25 = average of both turbine types; (2.3+2.2)/2

3.3 Barrage dam

3.3.1 Existing method

Fay and Smachlo (1983-I) showed that the barrage dam volume V_{dam} is not a function of the tidal range, but of the construction height H_c, which is shown by:

$$V_{dam} = m \cdot H_c{}^2 \cdot L_{dam} / 2 \quad (\text{m}^3) \qquad (3\text{-}16)$$

Where,
m = dimensionless slope of barrage walls or shores (-)
H_c = construction height according to existing model, in meters (m)
L_b = barrage length, in meters (m)

The cross section of the barrage dam was modelled as an isosceles triangle, without taking into account a crest width. For this case, it shows the barrage volume to be proportional to the square of construction depth H_c and proportional to the barrage length L_b.

It will, however, be preferable for a barrage dam to have a minimum required crest width for construction work (during construction) and connecting infrastructure during operation. Because formula 3-16 does not include a crest width, this method does not fulfil in this aspect. The new method will be used for further study.

3.3.2 New method

In the new model a save crest width of 10 m will be taken into account as a constant factor, where 8 m is the minimum space requirement for heavy vehicles (d'Angremond and van Roode, 2001). With the same height definition H_{dam} as for the sluice gates, this results in the barrage cross section A_{dam} and the total barrage volume V_{dam} shown in formula 3-17

$$H_{dam} = H_c \quad \text{(m)}$$

$$A_{dam} = 10 \cdot H_c + m \cdot H_c{}^2 \quad (\text{m}^2)$$

$$V_{dam} = L_{dam} \cdot A_{dam} = L_{dam} \cdot (10 \cdot H_c + m \cdot H_c{}^2) \quad (\text{m}^3) \qquad (3\text{-}17)$$

Where,
L_{dam} = barrage dam length, in meters (m)
A_{dam} = barrage dam surface area, in square meter (m^2)

The parameter m is the dimensionless slope of the barrage walls, as in 1:m. A value for m of 1.75 will be a representative value for further calculations.
The length of the dam is equal to the total barrage length minus the sluice and turbine lengths (4.4*$D_{turbine}$*$N_{turbine}$ as derived before).

3.4 Bed protection

Bed protection will be required when the subsoil is not able to resist the occurring flow velocities so that particles will be put in motion and even might be transported away. This should be avoided, as erosion could damage the construction. Bed protection should be considered for the turbining and sluicing process. The necessity of a bed protection will depend on the subsoil characteristics and on the flow velocity.

Subsoil

A large number of different subsoil types does exist, but for simplicity purposes these subsoil types will be categorised into two classes:

- Rocky material
- Other subsoil types (such as sand, clay etc.)

Rock is a cohesive material which could maintain high flow velocities. Thus, hardly any bed protection will be required for this type of subsoil. That means that no additional bed protection costs will be taken into account. This increases the attractiveness of the site.

The other subsoil types consist of non-cohesive and cohesive material, which are all strongly exposed to erosion. Whether erosion will actually occur depends on the largeness of the flow velocity.

Flow velocity during operation

The occurring flow velocity at the barrage with a subsoil other than rock should be estimated in order to determine the necessity and the amount of bed protection.

The flow velocity at the barrage can be calculated with the help of:

$$u = \sqrt{2 \cdot g \cdot h} \quad \text{(m/s)} \qquad (3\text{-}18)$$

During turbining, higher flow velocities will take place compared to the sluicing process. This is caused by larger head differences (see schemes section 2.2). The maximum flow velocity will take place at the largest head difference and the narrowest cross section. The maximum head, when generating a mean tidal range *R,* is 0.56*R* for One-way generation and 0.46*R* for Two-way generation (see Table 2.1). Because generation also continues during spring tide, head will exceed the mentioned values. *The maximum head when generating will therefore assumed to be equal to the tidal range R for both generation modes, about twice the values mentioned above.*

$$u_{(1)} = \sqrt{2 \cdot g \cdot R} \quad \text{(m/s)} \qquad (3\text{-}19)$$

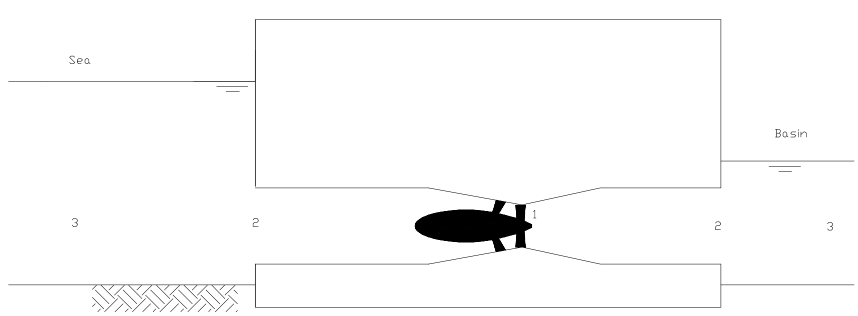


Figure 3.7 Turbine shaft cross section

The maximum flow velocity is the velocity taking place in the smallest cross section of the turbine shaft (1), see Figure 3.7. The discharge at point 1 should be equal to point 2 and 3, which are situated in larger cross sections. As a result, flow velocities will decrease from point 1 to 3. The turbine shaft space requirements for both types of turbines showed that the cross section at the runner blade (1) is about 4

times smaller as at the shaft entrance (2); $0.78D^2$ compared to $3D^2$. This means that the flow velocity at the shaft entrance should be 4 times smaller as at the turbine runner blade.
Bed protection, when required, will be placed on the subsoil starting at point 2 against the turbine caisson in the direction of point 3. The cross section at point 3 will largely depend on the site conditions (water depth). *Therefore, for simplicity purposes, the cross section at the bed protection location (3) will be assumed to be equal to point 2.* This means that a large safety factor is included in the application of the bed protection.

$$u_{(3)} = \tfrac{1}{4} \cdot \sqrt{2 \cdot g \cdot R} \quad \text{(m/s)} \tag{3-20}$$

To determine if the subsoil requires bed protection the Shields diagram will be used:

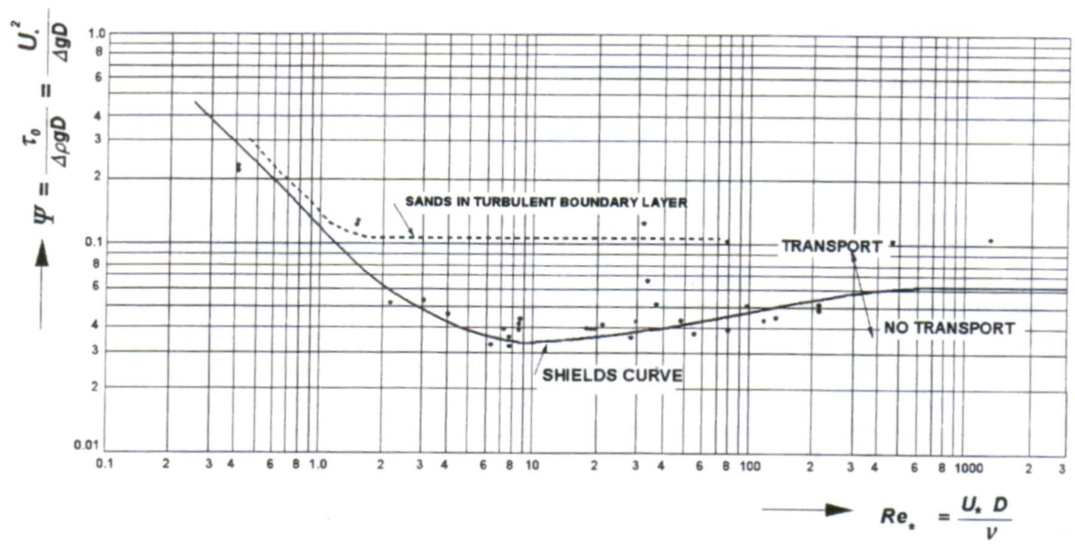


Figure 3.8 Shields diagram

The curve shows that values for the dimensionless parameter Ψ lower than about 0.03 (-), no transport will take place for all critical Reynolds values Re_* (-).

Required particle diameter $D_{part,req}$
The required particle diameter $D_{part,req}$ can be calculated by formula 3-21.

$$D_{part,req} \geq \frac{K_v{}^2 \cdot u^2}{K_s \cdot \Psi \cdot \Delta \cdot Ch^2} \quad \text{(m)} \tag{3-21}$$

Where;
$D_{part,req}$ = average required particle diameter, in meters (m)
K_v = dimensionless velocity/turbulence factor, indicating a load deviating from uniform flow (-)
u = flow velocity, in meters per second (m/s)
K_s = dimensionless strength-reduction parameter for stones on a slope (-)
Ψ = dimensionless Shields parameter (-)
Δ = dimensionless relative density, (for ρ_{part} of 2650 kg/m3 and ρ_{water} of 1027 kg/m^3) equal to 1.58 (-)
Ch = Chézy roughness coefficient, in square root meters per second (m$^{1/2}$/s)

With a Chézy coefficient assumed to be 40 m$^{1/2}$/s, u^2 can be rewritten as:

$$u^2 \geq u_{(3)}{}^2 = \tfrac{1}{16} \cdot 2 \cdot g \cdot R = 1.23 \cdot R \quad \text{(m/s)} \tag{3-22}$$

At both sides of the caissons, a flat bed level ($K_s = 1$) and high turbulence ($K_v = 3$) are considered :

$$D_{part,req} \geq \frac{2^2 \cdot 1.1 \cdot R}{1 \cdot 0.03 \cdot 1.58 \cdot 40^2} = 0.064 \cdot R \quad \text{(m)} \tag{3-23}$$

Formula 3-23 can be illustrated by:

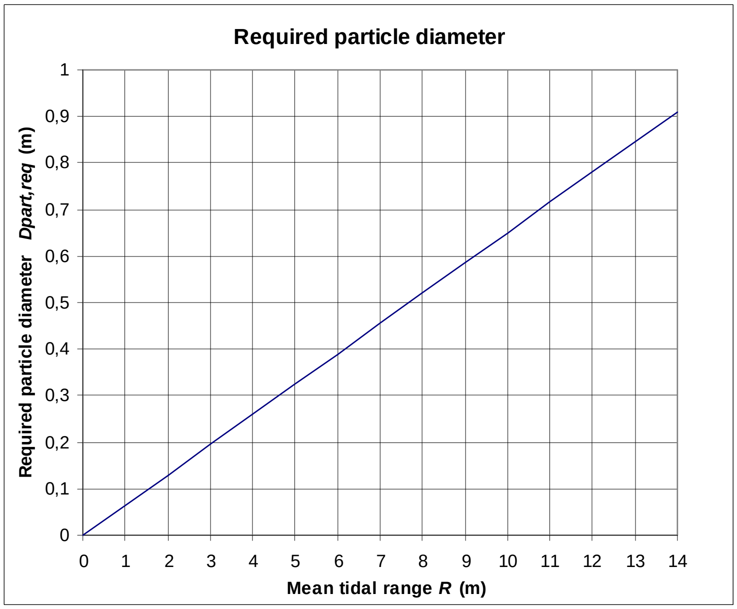


Figure 3.9 Required particle diameter as function of the tidal range

If the particle diameter of the subsoil is smaller than the required particle diameter for the mean tidal range on that site, bed protection is required. In that case the bed protection will at least have to consist of particle diameters larger than $D_{part,req}$.

Bed protection volume

To be able to define the bed protection costs C_{bed}, first the volume V_{bed} needs to be estimated and multiplied by the unit costs for bed protection material.

This phase includes some simplifications as it will be outside the scope of this study to make an accurate bed protection design; *the bed protection is assumed to consist of one single layer, meaning that no other filter layers or geotextile are to be taken into account.*

The bed protection volume V_{bed} can be written as:

$$V_{bed} = H_{bed} \cdot W_{bed} \cdot L_{bed} \quad \text{(m}^3\text{)} \tag{3-24}$$

This is illustrated in the figure below.

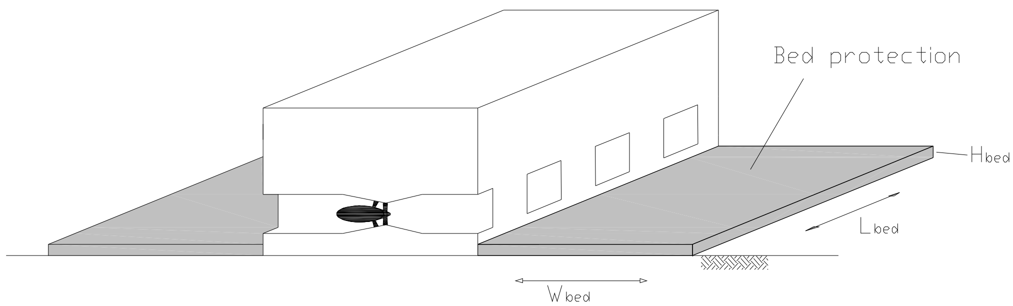


Figure 3.10 Position of bed protection

The single protection layer must be at least 2 particle diameters high, thus H_{bed} = 2*$D_{part,req}$ (d'Angremond and van Roode, 2001)). *The width of the bed protection at both sides of the turbine caisson will be assumed to have the same width as the caisson itself.* The powerhouse for a Bulb turbine is shown to be wider than for the Straflo turbine (subsection 3.1.2). This is on the other hand no reason to place a wider bed protection. The width at both sides will be a function of the flow velocity and turbulence. However, within this study for simplicity purposes a fixed bed protection width of 2 time 50 m will be considered.
As the bed protection will be placed in front of and behind the turbine and sluice gates caissons, without making a distinction in the bed protection dimensions at both places, the length of the bed protection will be determined by the total powerhouse and sluice gate length; $L_{bed} = L_p + L_s$.
Formula 3-24 can now be rewritten:

$$V_{bed} = (2 \cdot D_{part,req}) \cdot (100) \cdot (L_p + L_s) \quad (\mathrm{m}^3) \qquad (3\text{-}25)$$

3.5 Transmission lines

To be able to deliver the produced electricity from the power plant to the demand area or nearby electricity grid, this distance s_{grid} has to be bridged. Most common method is the application of transmission lines (for other alternatives see subsection 5.3.3). The more remote the tidal power plant location, the longer the transmission lines will be, increasing s_{grid}.

Where,
s_{grid} = distance from site to electricity grid, in meters (m)

3.6 Resulting plant design parameters

Since all civil work dimensions are worked out separately, the resulting plant design parameters are derived. These plant design parameters consist of site specific parameters and non-site specific parameters, summarized in the following table:

Table 3.1 List of resulting plant design parameters

Site specific parameters	Non-site specific parameter
$R_{MHWS\text{-}MLWS}$ $H_{wave,sign}$ $L_{barrage}$ H_0 $H_{sea,MLWS}$ $D_{part,req}$ s_{grid}	$N_{turbine}$ $D_{turbine}$ h_{rated}

All the information to derive the site specific parameters has been presented in this chapter. The three non-site specific parameters, from now on called plant design parameters, will be further elaborated in the next chapter.

Chapter 4 General turbine design

In the previous chapter, the general plant design described the general dimensions of the civil works for a tidal power barrage. As the turbines require further detailed study, this will be the handled in this chapter.
As turbines are directly linked to the generators and additional pumping was a point of further investigation, these will be included in the turbine design.

Objective:

- **Define a general turbine design**

Approach:

- **Define turbine design parameters**
- **Implement these parameters in the DTP Model**
- **Determine a general value for these parameters from the DTP Model results**

The chapter will start with a list of the different turbine design parameters which will be investigated in section 4.1. These will be divided into turbines and generators (section 4.2) and pumps (section 4.3). Section 4.4 will contain a turbine type suggestion per generation mode. Finally, in section 4.5 the operational interaction between turbines, sluice gates and pumps will be illustrated.

4.1 Turbine design parameters

Turbines and generators

The following turbine and generator parameters are included in the general turbine design:

- Turbine diameter $D_{turbine}$ (m)
- Number of turbine $N_{turbine}$ (-)
- Turbine efficiency $\eta_{turbine}$ (-)
- Generator efficiency η_g (-)
- Hydraulic losses in shaft k (-)
- Required head difference h_{req} (m)
- Rated power output P_{rated} (MW)

Pumps

In fact, a pump is nothing else than a turbine pumping up (or down) the water to (more rapidly) increase the head difference or reach the sea level. For clarification purposes, pumps are dealt separately from the turbines.
Whether or not pumps can produce more energy than they consume depends on the next pump parameters:

- Total pump surface area $A_{t,pump}$ (m^2)
- Pump capacity P_{pump} (MW)
- Starting head for pumping $h_{start,pump}$ (m)
- End head for pumping $h_{end,pump}$ (m)

The pump efficiency will be included in the turbine efficiency study

The use of pumps will not expect to increase the mean power output as pumps require power. For some scenarios, pumping may affect the mean power output in a positive way.

DTP Model implementation

The introduced parameters are implemented into the model, making it possible to look for the optimum design points for each of the parameters.

4.2 Turbines and generator

The possible tidal power turbine types will be briefly discussed, before analyzing the turbine design parameters.

4.2.1 Tidal power turbines types

Turbines are often categorized by mode of regulation. Regulation can be done by varying the position of the runner blades and/or guide vanes. The possible categories of turbines regarding the modes of regulation are:

- On/of turbines (no regulation)
- Single regulated turbines (variable runner blades or guide vanes (Gordon, 2001))
- Double regulated turbines (variable runner blades and guide vanes)
- Pump turbines (variable runner blades and guide vanes).

As mentioned in section 3.1, for tidal power only the following two reaction turbines remain a feasible types of turbines:

- Bulb turbine
- Rim type turbine (also called Straflo turbine)

Bulb turbine

The Bulb turbine is a horizontal unit with runners blades directly connected to the generator. The Bulb turbine is named after the shape of the watertight enclosure, see Figure 4.1.

Bulb turbines can be applied as single regulated, double regulated and pump turbines.

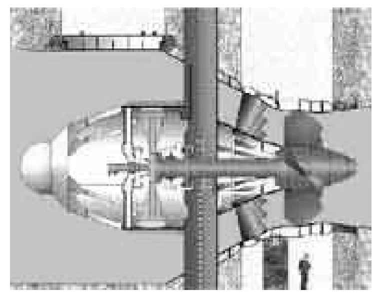


Figure 4.1 Bulb turbine (Alstom power)

Rim type turbine (Straflo)

The Straflo (straight flow) turbine is also a horizontal unit with a generator rotor mounted on the periphery of the turbine runner blades. The Straflo turbine, as called from now on, is a patented turbine by the Andritz group.

This type of turbine is only available as a single regulated turbine with variable guide vanes.

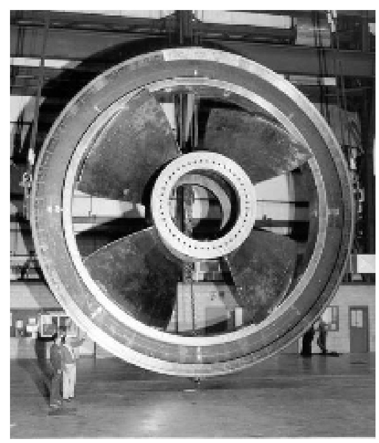


Figure 4.2 Straflo turbine (Andritz group)

Section 3.1 showed that the turbine type have influence on the powerhouse dimensions. As the efficiencies and costs for both turbines are not known yet, no preferable turbine can be suggested for now. This suggestion will be made in section 4.4.

4.2.2 Efficiencies and losses

As for each electricity source, also tidal power will have to deal with efficiency aspects and losses.
Three types of efficiencies and losses take place:

- Turbine efficiency $\eta_{turbine}$ (-)
- Generator efficiency η_g (-)
- Hydraulic losses k (-)

Their influence on the power output is illustrated by:

$$P = \rho \cdot \tfrac{1}{4} \cdot \pi \cdot D_{turbine}{}^{2} \cdot \sqrt{2} \cdot g^{3/2} \cdot h_{netto}{}^{3/2} \cdot \eta_{turbine} \cdot \eta_{g} \text{ (MW)} \tag{4-1}$$

With $$h_{netto} = h \cdot (1 - k) \text{ (m)} \tag{4-2}$$

Where,
h_{netto} = netto head difference, in meters (m)
k = dimensionless parameter for hydraulic losses in shaft (-)

This shows that the power output is linear proportional for both efficiencies and proportional to the square root for the hydraulic losses. The latter is thus less effective.

Turbine efficiency
Turbine efficiency $\eta_{turbine}$ is a dimensionless parameter and represents the potential energy in the water after being through the turbines divided by the starting potential energy.

As the variance in turbine efficiency over the discharge (or head difference) is turbine specific, both turbines types will have to be further investigated.
Both turbine types can be seen as a Kaplan turbine; the Bulb turbine as a single or double regulated Kaplan turbine and the Straflo turbine as a single regulated turbine with variable guide vanes (RETScreen). In the figure below a Bulb turbine is shown indicating the position of the runner blades and guide vanes.

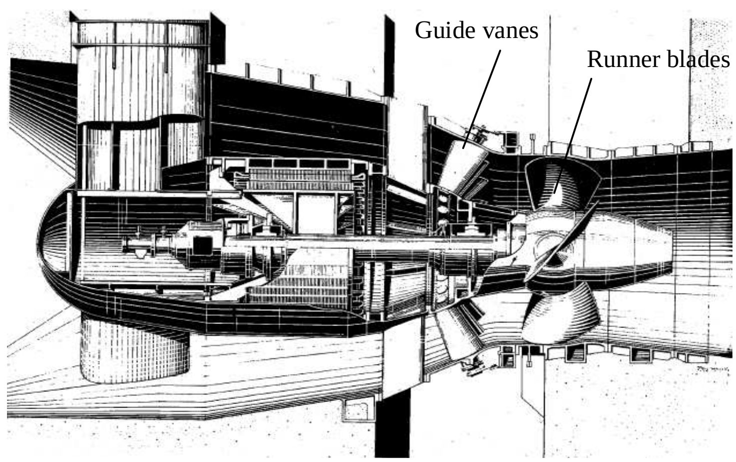
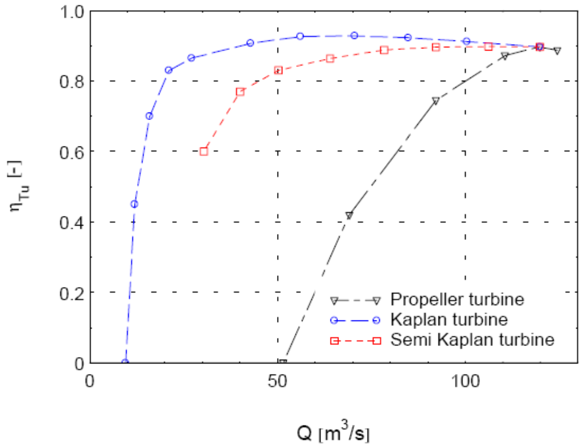


Figure 4.3 Illustration runner blades and guide vanes for Bulb turbine

The efficiency curves for all three turbine types, derived from experimental research, are shown in Figure 4.4 on the left.



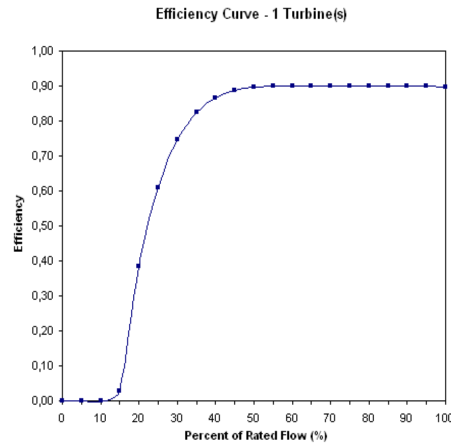


Figure 4.4 Turbine efficiency curve for three types of turbines (Knapp et al)

Figure 4.5 Turbine efficiency curve for Kaplan Turbine as percentage of rated flow (RETScreen)

Figure 4.4 clearly demonstrates the positive effect on the turbine efficiency of the variable runner blades of both Kaplan turbines, compared to the propeller turbine with only regulated guide vanes. A turbine without any regulation will be expected to be characterized by a straight line, starting at the same point as the other turbines and ending at level discharge of above 50 m^3/s.

As no efficiency curve for a single regulated Kaplan turbine with variable guide vanes was found, the Straflo turbine will be expected to be well described by the propeller turbine in Figure 4.4.

To be able to come to a reliable turbine efficiency for the Bulb and Straflo turbine, the discharges in Figure 4.4 should be transposed to a percent of the rated flow as per Figure 4.5.

Turbines require a minimum head difference to start operation, meaning that the percent of rated flow also requires a certain starting threshold. With the use of Table 4.6 (subsection 4.2.5) this point could be determined.

For One-way generation this point is about 55% of the rated flow (=0.28*R*/0.51*R*) and for Two-way generation this is about 66% (=0.28*R*/0.42*R*). Two-way generation require double regulated Bulb turbines, while for One-way generation single regulated turbines are sufficient, This information makes it possible to average the turbine efficiency over the rated flow (see Figure 4.6).

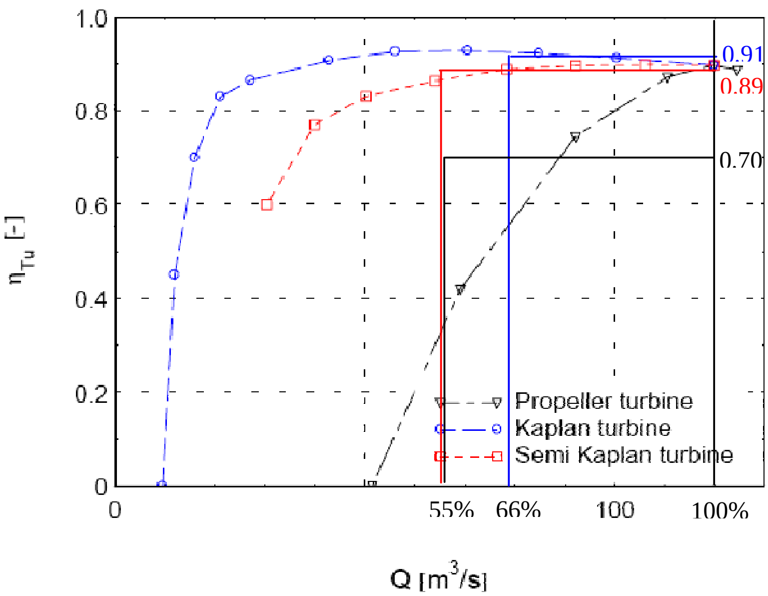


Figure 4.6 Turbine efficiency curve for 3 types of turbines as percentage of rated flow

In the table below, a summary is given for possible turbine types and operation for a tidal power plant. The results are as expected.

Table 4.1 Turbine efficiency for different turbine operations and turbine types

	Normal turbining direction	Reverse turbining direction	Pumping
Double regulated turbine (Bulb)	0.91	≈ 0.8 [6]	≈ 0.7 [4]
Single regulated turbine (Bulb)	0.89	< 0.8 [6]	< 0.7 [4]
Single regulated turbine (Straflo)	0.70	< 0.7 [6]	<< 0.7 [5]
Double regulated pump turbine (Bulb)	≈ 0.8 [6]	≈ 0.8 [6]	≈ 0.8 [6]

The double regulated turbine shows the highest efficiencies, except for pumping where the pump turbine scores the best. The pump turbine has about the same efficiency level for each type of operation. The Straflo turbine is the least efficient, caused by its fixed runner blades. **As Two-way generation is characterized by two turbining directions, averaging both direction will results in 0.85 (for a double regulated turbine).**

Generator efficiency

Generator efficiency η_g is a dimensionless parameter representing the amount of energy after being through the generator, divided by the energy coming through the turbines.

A generator efficiency of 0.95 is suggested (RETScreen).

Hydraulic losses

Besides the turbine and generator efficiency, also hydraulic losses k should be considered the turbine shaft. As these losses depend on the shape of the turbine shaft and each generation method has its own optimal shaft shape, it was not recommended to roughly estimate the possible hydraulic losses for these shape.

Alstom Power suggested a k value of 0.1 for normal flow direction (k_{in}) and 0.2 for reverse flow direction (k_{out}). **This results in a k_{one} of 0.1 for One-way generation and k_{two} of 0.15 for Two-way generation.**

DTP Model implementation

The following efficiencies and losses should have been used as input in the model:

Table 4.2 Averaged efficiencies and hydraulic losses per generation mode

	$\eta_{turbine}$	η_g	k
One-way generation	0.90	0.95	0.1
Two-way generation	0.85	0.95	0.15

However, as little information was available at that time, the efficiencies and loss were estimated. As a result, for a higher accuracy, the total efficiency (and thus power output) should be slightly decreased for One-way generation and slight increased for Two-way generation.

[4] (Wilson, 1970)

[5] Precise efficiency unknown, but certainly much less efficient than double regulated turbines

[6] According to Alstom Power France

4.2.3 Total turbine surface area

As turbines and generators form a large part of the project costs it will be valuable to optimize the total turbine surface area $A_{t,turbine}$. As this surface area is a function of the turbine diameter $D_{turbine}$ and the number of turbines $N_{turbine}$, finding an optimal relation between both design parameters and the site specific parameter will be the most important part of this optimum plant design study.

Turbine number and diameter

It was expected to be economical more attractive to install fewer larger turbines than a larger number of smaller turbine. This is confirmed by Alstom Power France.

Besides, the saving of the total powerhouse length L_p by using larger turbines can be replaced by the less expensive barrage dam.

Larger turbines also show higher turbine efficiencies compared to smaller turbines "*due to the lower effect of friction in large runners" (Gordon, 2001).* This is illustrated in the figure on the right.

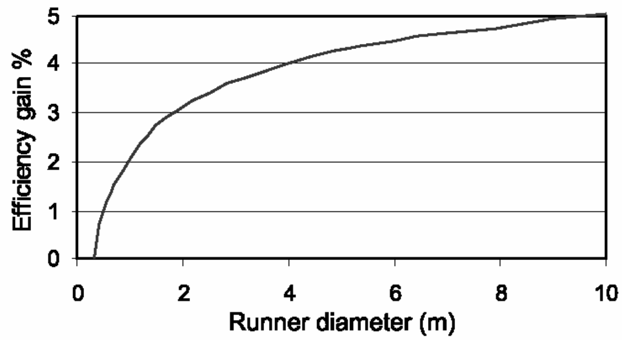


Figure 4.7 Turbine efficiency gain as function of turbine diameter (Gordon, 2001)

The increasing turbine efficiency makes it even more attractive to install a smaller amount of larger turbines. The turbine efficiency gain should however not be exaggerated; a turbine with a 8 m diameter only has 0.8 % higher turbine efficiency compared to a turbine with a diameter of 4 meter,

As a result, for the turbine costs and the total project costs it will be economically more attractive to install fewer larger turbines (assuming no excavation will be required). On the other hand, by looking at present tidal power plant and hydro power project**, the maximum possible turbine diameter applicable within this guideline will be 8 m[7].**

More information about turbine costs and further electrical equipment can be found in Appendix C1.

As mentioned in Chapter 3, turbine diameter can also be limited due to the tail water level in the basin. Excavation is not recommended due to the additional costs, but the same counts for too small turbine diameters. **With all the available information about costs and efficiencies, a minimum diameter of about 5 m is suggested.**

[7] Only the STPG made a feasibility study for the Severn tidal power project with turbines larges than 8 m, namely 9 m.

Then the following conclusion can be drawn:

Bulb turbine:

If $H_{sea,MLWS} \geq 18.4$ (m) then $D_{turbine} = 8$ (m)

If $11.5 < H_{sea,MLWS} < 18.4$ (m) then $D_{turbine} = \dfrac{H_{sea,MLWS}}{2.3}$ (m)

Else $D_{turbine} = 5$ (m)

Straflo turbine:

If $H_{sea,MLWS} \geq 17.6$ (m) then $D_{turbine} = 8$ (m)

If $11 < H_{sea,MLWS} < 17.6$ (m) then $D_{turbine} = \dfrac{H_{sea,MLWS}}{2.2}$ (m)

Else $D_{turbine} = 5$ (m)

Notice that a $H_{sea,MLWS}$ of 17.6 m and 18.4 m is very deep and not attractive from an economical perspective. But in case these depths do occur, a turbine diameter of 8 m is suggested.

DTP Model implementation

The model will be an usable method to find the optimum turbine surface area for One-way and Two-way generation. This will be done by fixing the turbine diameter and varying the number of turbines.

DTP Model results

With this model, various cases including different site specific parameters can be studied looking for similarities or patterns (see Appendix A4).
The total turbine surface area graph for Case 1 (Figure 4.8) and all other cases show a visual optimum in turbine number. Increasing the total turbine surface area will thus not automatically mean a larger power output. This optimum will be reached at a smaller amount of turbines for One-way generation than for Two-way generation. Because the head difference decreases increasing the number of turbines, applying a larger number of turbines will not always result in a higher power output.
Another aspect, see Figure 4.8, is the much larger mean power output (mean energy per tidal period) for the Two-way generation mode. Appendix A6 shows indeed a larger mean power output for Two-way generation plants starting at 19% up to 86%!

For maximum power output, the design number of turbines should be put on design point B for Two-way generation and at D for One-way generation.
For the most cost efficient tidal power plant a design point at 75% of the maximum design point will be suggested, which results for a specific Two-way generation scenario study by Delta Marine Consultants. *This factor is assumed to be equal for One-way generation.* These points are to be found in A and C.

Here;

A	= design point for cost efficient mean power $P_{mean,costopt}$ for Two-way generation
B	= design point for maximum mean power $P_{mean,maxopt}$ for Two-way generation
C	= design point for cost efficient mean power $P_{mean,costopt}$ for One-way generation
D	= design point for maximum mean power $P_{mean,maxopt}$ for One-way generation

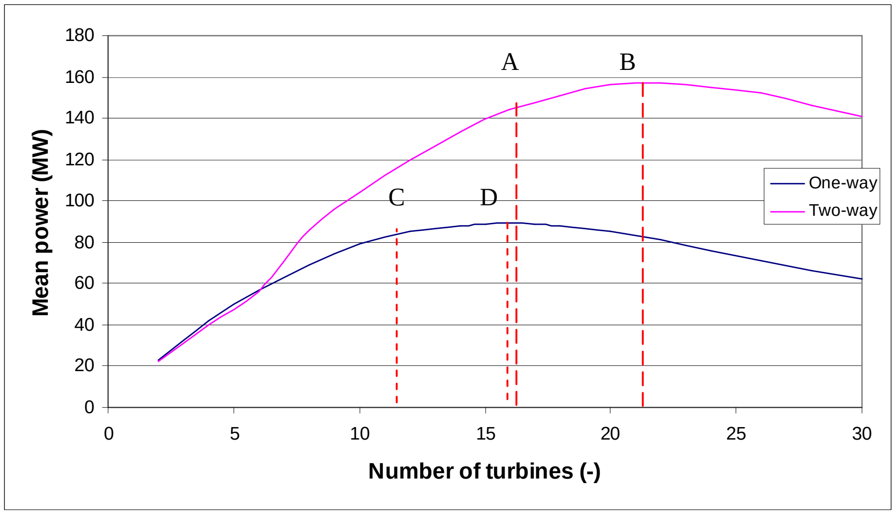


Figure 4.8 Example total turbine surface area curve

From different case studies, illustrated in Appendix B3, the turbine surface area factor α_A can be calculated with:

$$A_{t,turbine} = \alpha_{A,scheme} \cdot \frac{A_{bas,o}}{T \cdot \sqrt{2 \cdot g}} \cdot \sqrt{R} \quad (\mathrm{m}^2) \qquad \textit{(B-8)} \quad (4\text{-}3)$$

Where,

$A_{t,turbine} = \frac{1}{4} \cdot \pi \cdot D_{turbine}{}^2 \cdot N_{turbine}$, in square meters (m^2)

The results are demonstrated in the table below:

Table 4.3 Turbine surface area factors derived from scheme properties for different design points for One-way and Two-way generation

	One-way generation		Two-way generation	
	Maximum mean Power $P_{mean,maxopt}$	Cost efficient mean power $P_{mean,costopt}$	Maximum mean power $P_{mean,maxopt}$	Cost efficient mean power $P_{mean,costopt}$
$\alpha_{A,scheme}$	2.9	2.2	4.6	3.2

With the information from Table 4.3 it is possible to define the most cost efficient number of turbines:

One-way generation:

$$N_{turbine} = \frac{0.63 \cdot A_{bas,0} \cdot \sqrt{R}}{T \cdot D_{turbine}{}^2} \quad (-) \qquad (4\text{-}4)$$

Two-way generation:

$$N_{turbine} = \frac{0.92 \cdot A_{bas,0} \cdot \sqrt{R}}{T \cdot D_{turbine}{}^2} \quad (-) \qquad (4\text{-}5)$$

Where,

0.63 $= \dfrac{\alpha_{A,one} \cdot 4}{\sqrt{2 \cdot g} \cdot \pi \cdot D_{turbine}^{\ 2}}$ and 0.92 $= \dfrac{\alpha_{A,two} \cdot 4}{\sqrt{2 \cdot g} \cdot \pi \cdot D_{turbine}^{\ 2}}$

This shows that Two-way generation requires almost 50% extra turbines. However, this will be compensated by the 71% larger mean power output (see Appendix A6).

4.2.4 Design power output

The plant capacity should be higher than the potential power P_{pot} of a site (see section 5.2) to be able to generate this (mean) potential power, as tidal power can not be generated at all times.

The design capacity limits the maximum amount of power by restricting some turbine and generator parameters. The higher this limitation the larger the power generation, till the potential of a site is fully exploited.

The amount of Power generated by the turbines can be described according to:

$$P = \rho \cdot g \cdot Q \cdot h_{netto} \cdot \eta_{turbine} \cdot \eta_g \cdot 10^{-6} \quad \text{(MW)} \tag{4-6}$$

Where $Q = A_{t,turbine} \cdot \sqrt{2 \cdot g \cdot h_{netto}}$ (m^3/s) and $h_{netto} = h \cdot (1-k)$ (4-7)

Thus $P = \rho \cdot A_{t,turbine} \cdot \sqrt{2} \cdot g^{3/2} \cdot h_{netto}^{\ 3/2} \cdot \eta_{turbine} \cdot \eta_g \cdot 10^{-6}$ (MW) (4-8)

Where,
Q = discharge, in cubic meters per second (m^3/s)

- If the generator output, which is directly connected to the turbine, is higher than the amount of power the turbine can produce, then the power output is limited by the turbine.
- If the generator output is lower than the amount of power the turbine can produce, then the power output is limited by the generator. This limitation is more often the case.

The power output on which turbine and generator are restricted / designed is called “rated power”.

The plant capacity can now be formulated as follows:

$$P_{capacity} = P_{rated} \cdot N_{turbine} \quad \text{(MW)} \tag{4-9}$$

Where,

$$\boxed{P_{rated} = \rho \cdot g \cdot Q_{rated} \cdot h_{rated} \cdot \eta_{turbine} \cdot \eta_g \cdot 10^{-6} \quad \text{(MW)}} \tag{4-10}$$

Where,
Q_{rated} = rated discharge, in cubic meters per second (m^3/s)
h_{rated} = rated head (over turbines), in meters (m)

To maintain a certain economic attractiveness, the capacity is often limited to output level lower than the maximum power output.
For the general plant design, the following three levels of rated power levels will be elaborated:

- Maximum rated power
- Rated power for tidal power plants nowadays
- Most economic attractive rated power

Whether the third level will differ from the second will be investigated with the help of the DTP Model.

Maximum rated power
Power generation designed on maximum rated power has the objective to fully utilize the site's capacity. Maximum power output can be obtained when head differences are largest, thus at the largest tidal range, taken to be $R_{HHWS\text{-}LLWS}$. As a result, turbines and generators are to be designed on this maximum design level. As this design tidal range has a rare occurrence, designing turbines and generators at this power output level is not interesting from the economic point of view.

Because a plant design at maximum rated power will not increase the feasibility of tidal power, this rated power level will not be worked out further.

Rated power for tidal power plants nowadays
As just described, for economic reasons tidal power plants will not be designed to generate maximum power output as it will be economic inefficient to generate below these tidal peaks.
With the available data from operational tidal power plants and tidal power plant studies it will be possible to check their rated power level.

Tidal power plants can expect to be designed on an output level able to generate at (more frequent) large head differences just below the rare extreme head differences. A realistic upper limit for power generation is the power output at mean spring tidal range $R_{MHWS\text{-}MLWS}$, which has a more frequent occurrence than at $R_{HHWS\text{-}LLWS}$.
With the use of formula 4-10 this level for rated power can be compared with the real installed capacity per turbine for four tidal power projects. The study results are illustrated by Table 4.4, with efficiencies and losses from subsection 4.2.2, and are based on the modelled generation schemes from Appendix B1.

Table 4.4 Rated power (per turbine) for different tidal power projects

Project	Generation mode	*Installed* Power P (MW)	Diameter $D_{turbine}$ (m)	Tidal range $R_{MHWS\text{-}MLWS}$ (m)	*Modelled* Head factor (-)	*Modelled* Rated power P_{rated} (MW)	Ratio (-)
Mersey	One-way	25	8	8.4	0.68	26.2	1.05
Sihwa	One-way	25.4	7.5	7.8	0.68	20.6	0.81
Severn	One-way	60	9	12	0.68	56.6	0.94
La Rance	Two-way	10	5.35	10.9	0.48	9.7	0.97

The final ratio between the modelled rated power, with the head factor[8] from the generation scheme models (derived from operational plants and feasibility studies in Appendix B1) and the installed amount of power, shows that the rated power at $R_{MHWS\text{-}MLWS}$ is realistic for three of the four projects. As for Sihwa, generation of tidal power is not the only main objective, no valuable conclusion can be drawn for this project for the most economic attractive rated power.
As a result, **a tidal power plant with rated power at mean spring tidal range is realistic.**

Most economic attractive rated power
This design power output will have to result in the lowest construction cost per power ratio r_{costs} (in \$/MW) as will be discussed in Chapter 5. For a given site, the total plant capacity depends on the turbine surface area and the sluice gate surface area, but they also influence the project construction costs. The DTP Model will hopefully show how to reach this most economical point for rated power, regarding the number of turbines.

[8] The head factor is the factor indicating the maximum head difference for the generation schemes. The head factor for example for One-way generation is 0.68 as the maximum head is $0.68R$

DTP Model implementation
The model will most likely show whether the presently used level of rated power for tidal power plants is the most economic attractive or not. If not, an new rated power level will have to be checked.

DTP Model results
The model follows the statement made earlier on that power output can be limited by the generator capacity, as shown in Figure 4.9. If, without generator capacity boundary, the mean power output finds itself on the horizontal part of the rated power curve, it will be cost efficient to limit the rated power by defining an upper level generator capacity. For maximum power output, the design number of turbines should be put on design point B for Two-way generation and at D for One-way generation.
As for the total turbine surface area, for the most cost efficient tidal power plant a design point at 75% of the maximum design point will be suggested. These are point A and C.
At the design points B and D the point is reached where the turbine limits the power output. Therefore, increasing the rated power above this level is not effective and worthless.

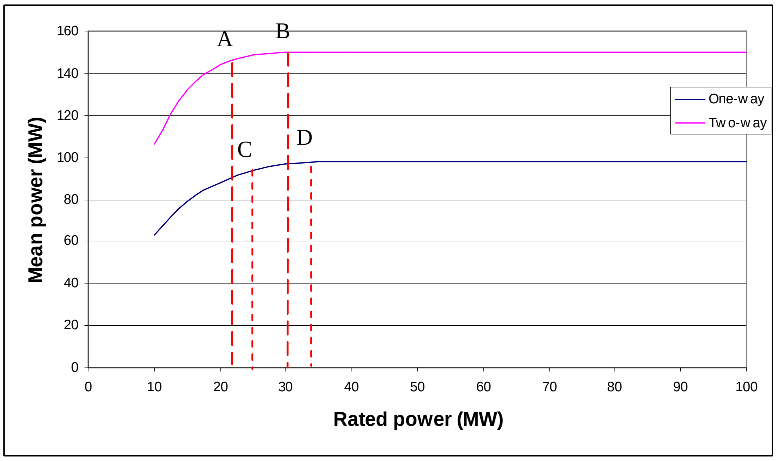


Figure 4.9 Example rated power curve

According to the results from the DTP Model and with the help of formula 4-8 the following design head difference will determine the rated power (with the operational and study scheme results from Appendix B1 as comparison):

Table 4.5 Rated head differences determining generator capacity (see Appendix A4 and B1)

Design point	DTP Model scheme		Operation plant scheme	
	One-way	Two-way	One-way	Two-way
A&C	0.51R	0.42R	0.68$R_{MHWS\text{-}MLWS}$	0.48$R_{MHWS\text{-}MLWS}$
B&D	0.62R	0.51R	0.68$R_{MHWS\text{-}MLWS}$	0.48$R_{MHWS\text{-}MLWS}$

As it is impossible to compare mean tidal ranges with mean spring tidal ranges, the different rated heads for the two schemes can not be compared with each other. As the values for the DTP Model scheme offers more background and is expected to be more accurate, these values for the rated head will be used for further study.

4.2.5 Required head difference

From the generation schemes derived from operational plant and feasibility studies (as determined in Appendix B1), a required tidal head difference h_{req} as function of the mean tidal range was found: 0.32R.

DTP Model implementation
By using the DTP Model, it can be checked whether the suggested relation with the mean tidal range is reliable and if 0.32*R* is indeed optimal.

DTP Model results
From the model, for all cases it can be concluded that (indeed) **the required head difference is to be seen as function of the mean tidal range (0.28R)**, shown below in Table 4.6 and Figure 4.10.

Table 4.6 Required head difference (see Appendix A4)

	One-way generation	Two-way generation
h_{req} (m)	0.28*R*	0.28*R*

These values approach the earlier suggested head difference of 0.32*R* and do in fact not differ with the mode of operation as found earlier. The figure also clearly demonstrates that by taking a constant h_{req} of 2 m, as sometimes considered, the mean power output for this case has not reached the optimum design point yet. Alstom Power agreed that a fixed h_{req} of 2 m is not optimal for all sites.
Note that no additional costs are required to shift this h_{req}. **In fact, optimizing the required head difference is the only way of increasing the mean power output without financial consequences**.

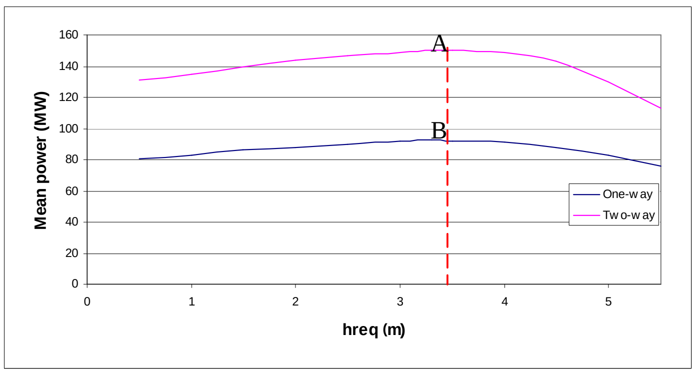


Figure 4.10 Example required head difference curve

4.3 Pumps

One of the main uncertainties in the tidal power generation process is the (additional) value of applying pumps (pump turbines) into the system. The La Rance tidal power station uses pumps when tidal range is (too) small, which is most probably necessary to cope with a minimum energy supply guarantee. Whether this makes the plant more profitable is uncertain.
Also the additional costs for a pump turbine are unknown, as no research has been done. But these are just loose questions distracting **the main goal; does pumping increase the mean power output?**

As introduced was in section 4.1, the following parameters have to be involved:

- Total pump surface area $A_{t,pump}$ (m^2)
- Pump capacity P_{pump} (MW)
- Starting head for pumping $h_{start,pump}$ (m)
- End head for pumping $h_{end,pump}$ (m)

Total pump surface area
The number of pump turbines can not exceed the number of generating turbines. It will on the other hand still be possible to install less pump turbines. This results in:

$$A_{t,pump} \leq A_{t,turbine} \qquad (\mathrm{m}^2) \qquad (4\text{-}11)$$

Pump capacity
For now, pump capacity is assumed to have the same amount of MW's as the generator capacity. Only when pumping will seem to be profitable, further study will have to determine the relation between the two capacities.

Starting and end head for pumping
The pumping process has been conscious separated into two sub-processes:

- Downward pumping
- Upward pumping

Here, downward pumping is the process of pumping in the direction of gravity, opposite from upward pumping against gravity (see Figure 4.11 and 4.12).

Upward pumping is used for the La Rance power plant; downward pumping has not (yet) been utilized for tidal power. The latter could be advantageous, due to the fact that with the same pump capacity (MW) higher discharges can be generated.
Whether one will be more profitable than the other will be investigated with the help of the DTP Model.

The start of the pumping process is described by the starting head $h_{start,pump}$, while the end head $h_{end,pump}$ defines the moment the pumps stop functioning. Both are illustrated in Figure 4.11 and 4.12.

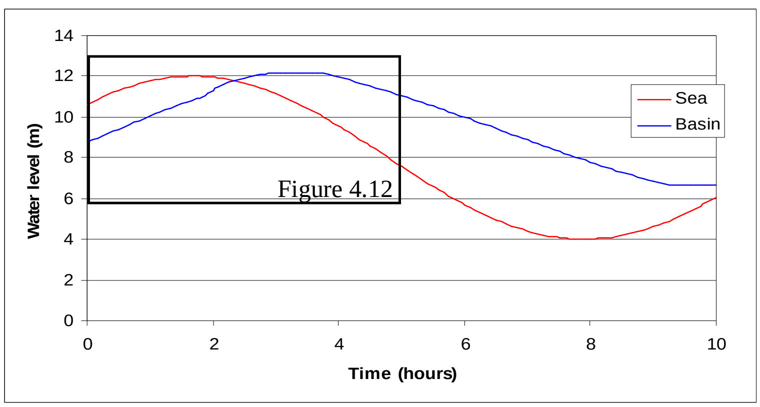


Figure 4.11 Overview downward and upward pumping process

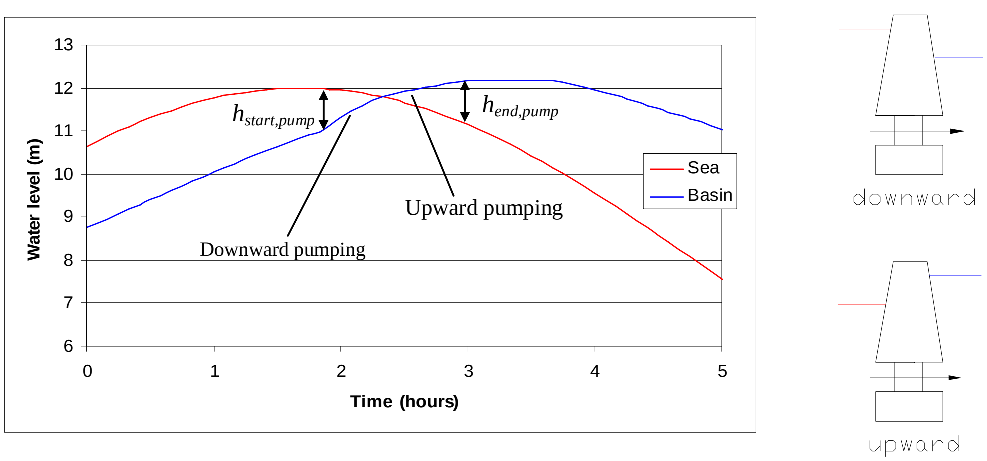


Figure 4.12 Closer view downward and upward pumping process

DTP Model implementation

The model will be expected to demonstrate whether additional pumping will be favourable or not. Then, the four introduced pump parameters together with a pump efficiency of 0.7 for a double regulated Bulb turbine (see Table 4.1) are required as input parameters. This type of turbine was considered because of the fact a that time little information was available about the special designed pump turbines.

DTP Model results

To check the benefit of pump turbines and sluice gates, the next eight scenarios were introduced for the four cases:

Table 4.7 Applied DTP Model scenarios

Scenarios	1	2	3	4	5	6	7	8
Sluice gates:	✗	✓	✓	✓	✓	✗	✗	✗
Pumps downward:	✗	✗	✓	✗	✓	✓	✗	✓
Pumps upward:	✗	✗	✗	✓	✓	✗	✓	✓

The DTP Model shows for Case 1 (for specifications see Appendix A4) the following results for One-way generation (Figure 4.13) and Two-way generation (Figure 4.14) with $h_{start,pump} = 1$ and $h_{end,pump} = 1$:

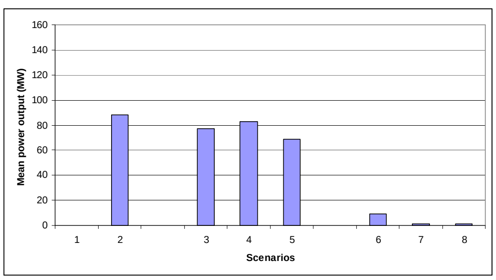


Figure 4.13 Different One-way scenarios for Case 1

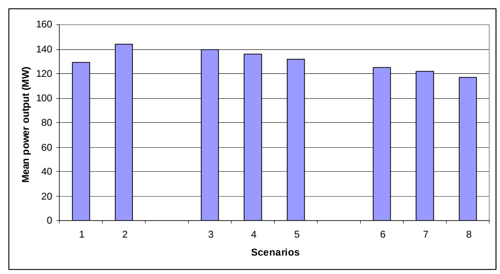


Figure 4.14 Different Two-way scenarios for Case 1

The other studied cases show the same trend as the two preceding figures, making it possible to draw the following conclusions:

For One-way generation

- **Sluice gates are required**
  (compare scenario 1 → 2)
- **Pumping does not increase the mean power output**
  (compare scenario 3,4,5,6,7,8 → 2)

For Two-way generation

- **Sluice gates are not required, but do increase the mean power output substantially (10%)** (compare scenario 1 → 2)
- **Pumping with sluice gates does not increase the mean power output without pumping**
  (compare scenario 3,4,5 → 2)
- **Pumping without sluice gates does not increase the mean power output without pumping** (compare scenario 6,7,8 → 1)

As for One-way generation sluice gates must be installed, the most potential pumping scenario with sluice gates for One-way generation (scenario 4) was further elaborated to recheck the profitability by changing parameters. The same was done for Two-way generation for scenario 6; from which could be investigated whether a plant with pumps could replace the sluice gates and produce the same amount of power.

This has been done by varying the $h_{start,pump}$ and $h_{end,pump}$. The effect on the mean power output is illustrated in the figures below.

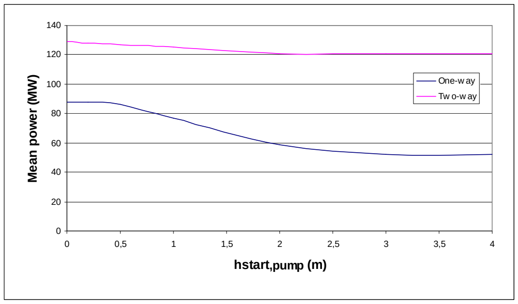


Figure 4.15 $h_{start,pump}$ curve

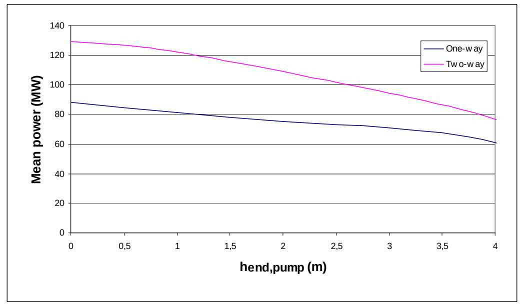


Figure 4.16 $h_{end,pump}$ curve

As expected, the curves in Figure 4.15 ends with a horizontal line, due to the fact that the starting head can not exceed the available head. Thus, continuously increasing the starting head for pumping has no effect as the pumps can not start earlier than when the available head has been reached.
Figure 4.16 do not show a horizontal end of the curves, as the end head is not restricted in any way.

Increasing these parameters results in a lower mean power output, meaning that no cost efficient scenario could be found where pumping has a positive effect on the energy production.

Note that the electricity rates are taken constant.
At the points the lines reaches the y-axis (the situation without pumping) the curve's derivative approaches zero. This indicates that, in case electricity rates during pumping are very low compared to what is electricity generation could bring up, at night, pumping could be viable.
Also, as this study did not apply the special designed pump turbines, higher pump efficiencies (about 14 percent) can be reached. This increases the profitability of pumping, but decreases the efficiencies for generating.
However, combining pumping with low electricity rates is not always possible and requires good planning in case it might be.
The following conclusion with respect to pumping can be drawn:

- **Pumping is not profitable at constant electricity rates**
- **Pumping can be profitable in times of low electricity rates (for example at night)**

4.4 Suggested turbine type per generation mode

All the necessary information to come to valid comparison of the different turbine types have been introduced, with differences in:

- Efficiencies
- Costs (Appendix C1)

As pumping was shown not to be profitable, pump turbines will not be taken into account.
The following turbine types can be applied for One-way generation:

- Straflo turbine
- Single regulated Bulb turbine
- Double regulated Bulb turbine

Due to low efficiencies of most of the turbines types, for Two-way generation one turbine is by far the best option:

- Double regulated Bulb turbine

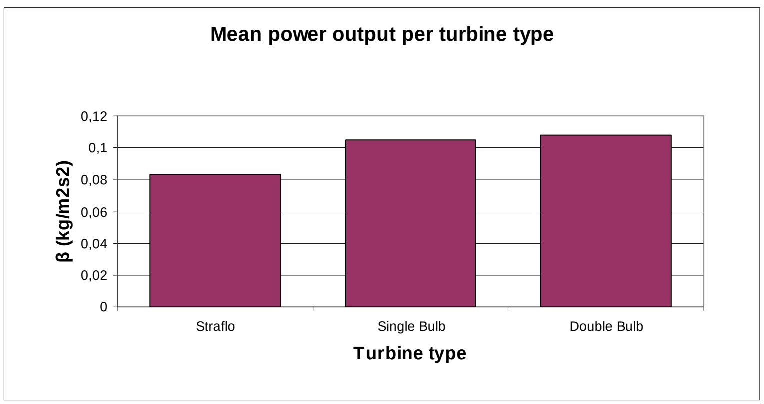
This means that only the turbine types feasible for One-way generation require a selection.

Costs
Turbine costs: Double regulated turbines are about 10% more expensive than single regulated turbines (see Appendix C1)
Powerhouse costs: The powerhouse costs for Bulb turbines are about 40% higher than for Straflo turbines (see Appendix C1)

Efficiencies
As shown before, efficiency has a large influence on the power output.
With the efficiencies from Table 4.1 and an equal number of turbines, it is possible to show the following power output distribution by the same method as derived in Appendix A6, using β. β is the power output parameter and $P_{t,mean/T}$ is the mean power output per tidal period. The table clearly shows the effect of the low efficiency of the Straflo turbine on the mean power output.

Table 4.8 Power output per tidal period per turbine types

	Straflo turbine	Single regulated Bulb turbine	Double regulated Bulb turbine
$P_{t,mean/T}$	β = 0.08	β = 0.10	β = 0.11
As ratio	1	1.27	1.30



Results
With these findings, it is possible to determine the costs per power ratio C_t /P per turbine type. This ratio is the most valuable method to compare the types of turbines; the lower the ratio the more economical attractive. The calculation is illustrated in the table below:

Table 4.9 Comparison different turbine types

	$C_{turbine}$	C_p	$\mathbf{C_t}$	P	$\mathbf{C_t/P}$
Straflo turbine	0.9	0.6	**1.5**	1	**1.50**
Single regulated Bulb turbine	0.9	1	**1.9**	1.27	**1.50**
Double regulated Bulb turbine	1	1	**2**	1.30	**1.54**

Remarkably, the costs per power ratio for the Straflo and the single regulated Bulb turbine are exactly the same. So this method could not give the solution.
However, besides the economical aspects, there are some other criteria on which a turbine could be selected.

As the Straflo turbine is a patented turbine, it can only be constructed by one turbine producer. The Bulb turbine on the other hand has the huge advantage that it can be fabricated all over the world, which could save time and perhaps money due to competition.
Besides, a rim type of turbine as the Straflo has shown difficulties and problems around the water tightness of the generation. Also the cooling of the generator is much easier for the Bulb turbine as it is surrounded by cold water.

With this, the single regulated Bulb turbine is preferred and suggested above the Straflo turbine. Therefore, the Straflo turbine will be kept out from the Generic Plant Design Guideline.

Thus, for One-way generation the single regulated Bulb turbine is suggested and for Two-way generation the double regulated Bulb turbine.

The resulting Generic Plant Design Guideline can be found in Appendix D.

4.5 Operational interaction between turbines, sluice gates and pumps

This section will demonstrate the operational interaction between the turbines, sluice gates and pumps by using the DTP Model results.
As the DTP Model used separate models for One-way generation and Two-way generation, their results will be consequently discussed separately.

4.5.1 One-way generation

For pumping, 1 m downward pumping and 1.5 m upward pumping was applied in the following illustrations.
The water levels inside and outside the basin for one day are shown in Figure 4.17 (case 1). The large sluice gate surface area makes it possible for the inside basin level to follow the outside water level when sluicing.
The effect of pumping (downward and upward) on the inside water level is obvious (in one direction).

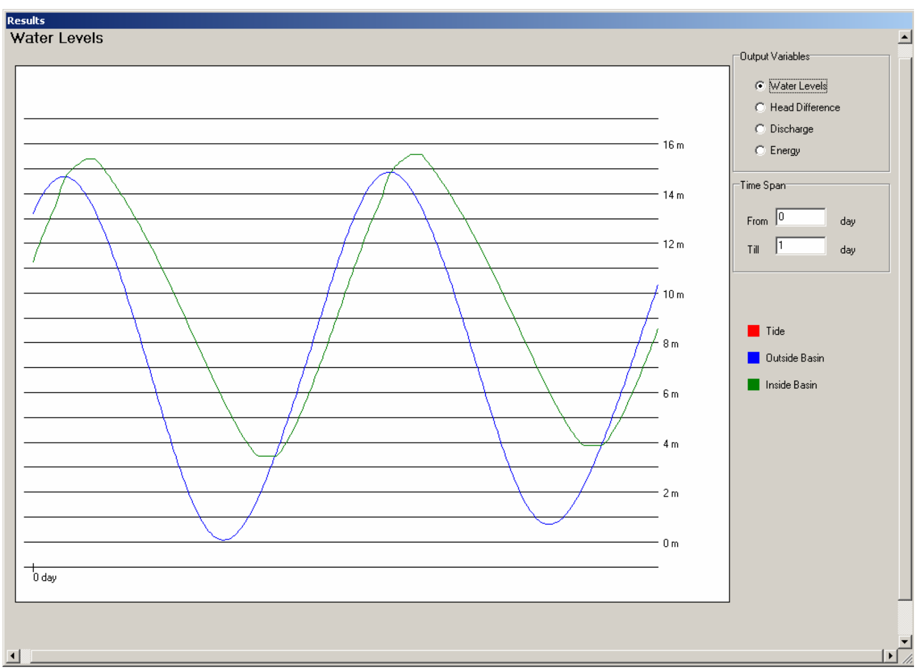


Figure 4.17 Water levels inside and outside basin(One-way generation)

The related discharges can be found in Figure 4.18, where the sluice gates collaborate with downward pumping, after each generation period.

The figure clearly shows, logically, higher discharges for downward pumping than for upward pumping.

As turbines require a minimum head of 2 m, also the turbine discharges start at a certain discharge level, in contrary to the sluice gates and pumps.

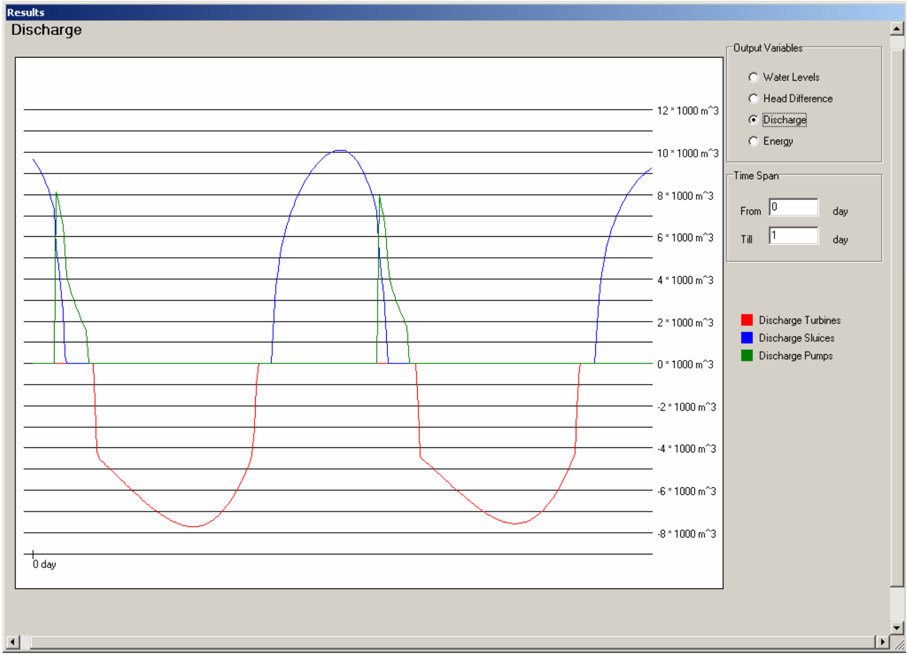


Figure 4.18 Discharges (One-way generation)

From the discharges it is possible to plot the power output for generation and input (negative output) for pumping. As the turbines and pumps include a rated capacity, their maximum power output/input are flattened out (discussed in subsection 4.2.4). This is illustrated in Figure 4.19.

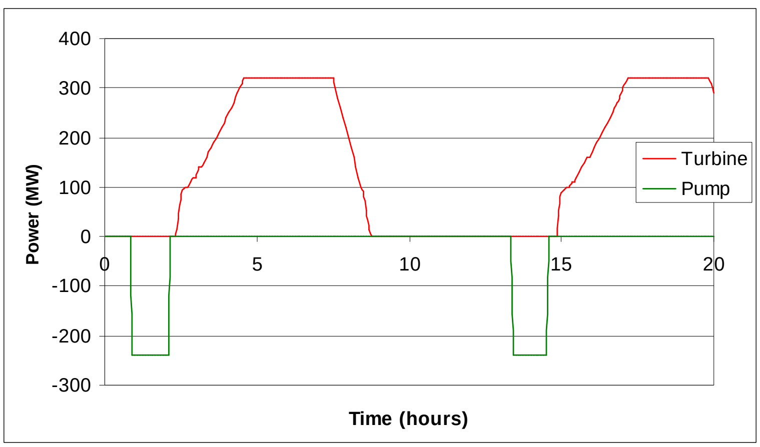


Figure 4.19 Power input /output (One-way generation)

4.5.2 Two-way generation

The water levels inside and outside the basin for one day are shown in Figure 4.20 (case 1). In contrary to a One-way generation mode, pumping is here in both directions.

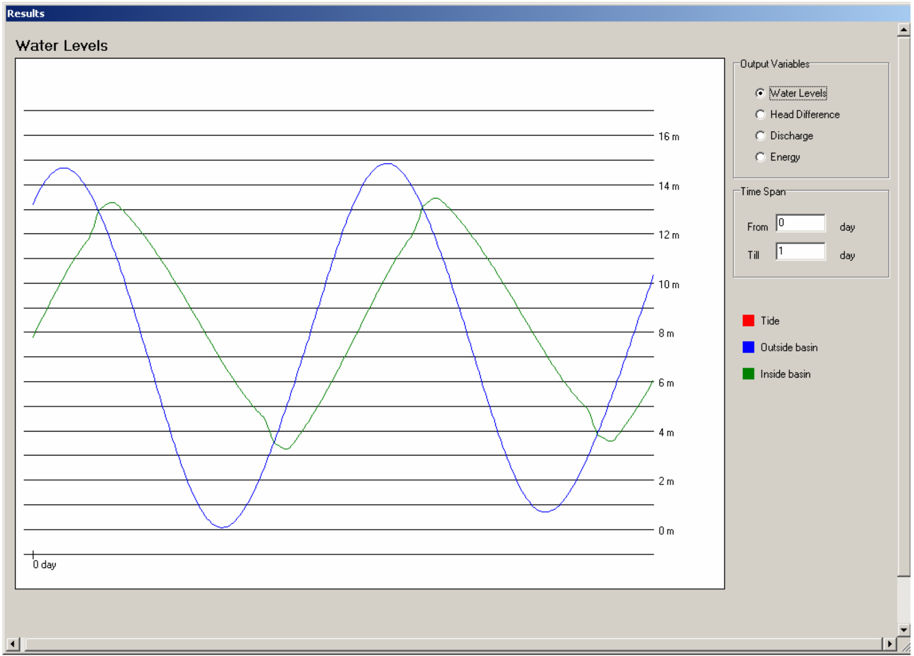


Figure 4.20 Water levels inside and outside basin (Two-way generation)

The discharges during sluicing for Two-way generation are much lower than for One-way generation. Section 3.2 already mentioned the requirement of sluice gates for One-way generation, while for Two-way generation the function of the sluice gates can be replaced by the turbines generating in two directions. This is proven by Figure 4.21.

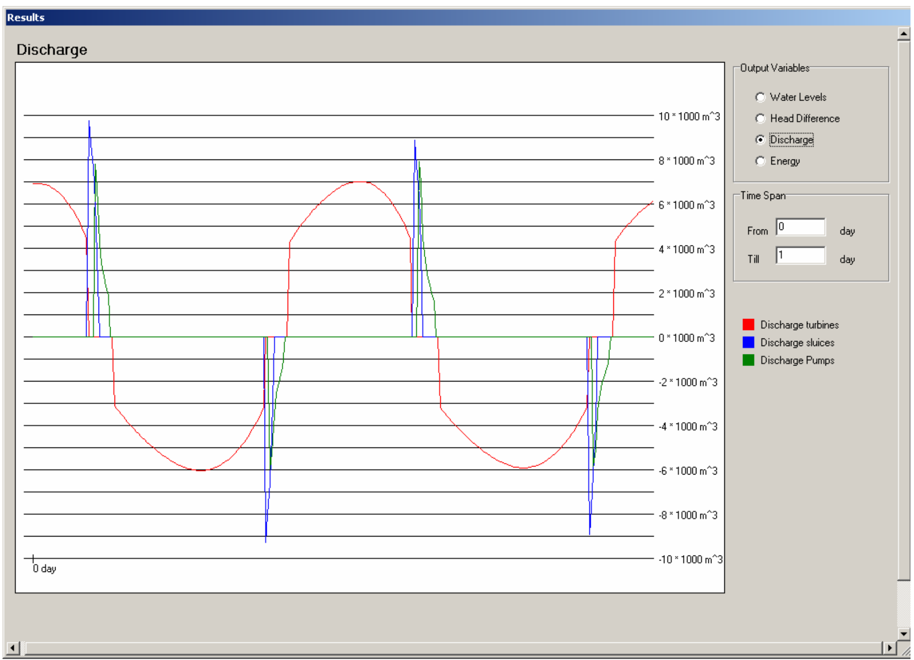


Figure 4.21 Discharges (Two-way generation)

Two-way generation is characterised by a better power distribution over a day compared to One-way generation, as can be seen in Figure 4.22.

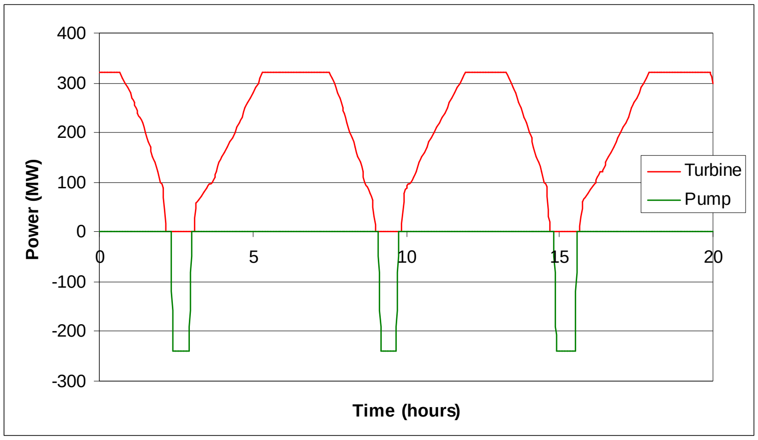


Figure 4.22 Power input /output (Two-way generation)

These illustrations have been used for understanding purposes, showing the impact of the different turbine design parameter worked out in this chapter.

Chapter 5 Site selection aspects

Now that the generic design guideline was drawn up, next step is to look for a feasible location for a tidal power plant; this phase is called site selection. But what makes a site promising for tidal power? Each site has its own parameters, such as the basin surface area, tidal range and water depth. Which specific parameters will influence the potential of a site and at what effect?

The objectives and approach of this chapter will be as follows:

Objectives:
- **Work out the essential site selection aspects for the site selection process**
- **Determine criteria required for a feasible site**

Approach:
- **Check which selection aspects will describe the potential of a site**
- **Define which of these aspects will be taken into account**

Final goal is to draw up a Generic Site Selection Guideline, which will have the following structure:

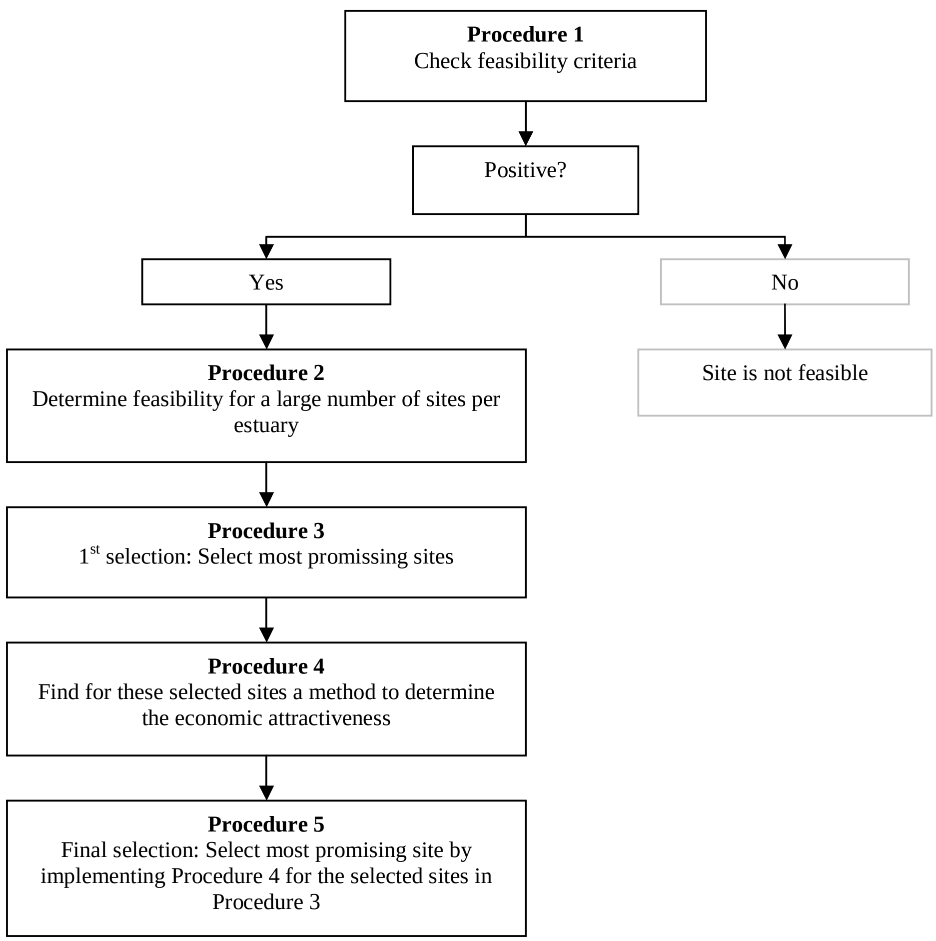


Figure 5.1 Build-up of Generic Site Selection Guideline

A scenario where such a site selection guideline could be valuable is for example; to help a government, interested in electricity generation by tidal power, to find promising sites (or the most promising site).
This chapter will describe all the required procedures resulting in a valuable site selection and site selection guideline. Section 5.1 will introduce the essential site selection aspects. In the following section the potential power (5.2), the electricity supply (5.3) and the soil properties and flow velocity during closure (5.4) will be worked out. In section 5.5 some additional site selection parameters will be presented simplifying the site selection process, where in section 5.6 the resulting feasibility criteria will be described.

5.1 Essential site selection aspects

One of the major aspects of a tidal power plant is the **technical aspect** for each site, taking into account the constructional and operational aspects.
But at what costs will tidal power be acceptable? A location with the same amount of potential power, however somewhat less expensive, will logically be preferred above the more expensive alternative. This means that economics should be taken into account in the site selection; the **economical aspects** of the project.

Normally, also environmental impacts should be included in the site selection process.
With this, environmental impacts such as the influence on the basin surface area and level, the fish habitat and the surrounding morphology should have been considered. These however, are hard to predict and to evaluate in comparison with the technical and economical aspects and will therefore be neglected.
The fact that the environmental impacts will be outside the scope of this study is unavoidable and regrettable as they have an enormous influence on the final feasibility.

5.1.1 Technical aspects

Technical feasibility includes an enormous amount of aspects which defines this feasibility for a site. Before continuing to the aspects that will be worked out further in detail, some simplifications will be made:

Simplifications for construction:

- *Construction material, equipment and personnel are available*
- *Isolated location of site has no effect on construction material, equipment and personnel*
- *Construction material, equipment and personnel are equally priced for all potential sites*
- *Construction height is not limited*

Simplifications for operation:

- *There is an existing demand for electrical power*
- *Educated operational personnel is available (and equally priced for all possible sites)*

After these assumptions, the three technical aspects of a tidal power project will be further elaborated:

- Potential power
- Electricity supply
- Soil properties and flow velocity during closure

Potential power
The potential power is the amount of power that could be generated at a specific site and can be calculated as the average power output over a tidal period. It is a valuable characteristic, making it able to check the attractiveness of a given site. The larger the potential power, the more energy can be produced.

Electricity supply
As a tidal power plant generates electricity, this electricity needs to be transported. In case there is access to an electricity network, electricity can easily be transported via this grid. If a promising site is isolated from an electricity network, other solutions are available such as the conversing into other electricity sources or to temporarily store energy.

Soil properties and flow velocity during closure
The influence of local soil properties and flow velocities during closure of dams at potential sites will affect the technical feasibility of the whole project. Both should therefore be included as an essential aspect during site selection.

The effect of climate conditions such as extreme low temperatures, resulting in the forming of sea ice and influencing the project construction and operation, will not be taken into account. A possible river inflow in the tidal basin is also neglected, which can result in a slight increase of basin level, as this river discharge is negligible compared to the discharge flowing in and out through the turbines and sluice gates. In addition, the basin water level could easily be controlled during operation.

5.1.2 Economical aspects

As for each project, economic feasibility plays an important role in the total feasibility of a project. For simplicity purposes, the following assumptions are made:

- *Capital costs will only comprise the construction costs for the powerhouse, turbine-generator, sluice gates, barrage dam, bed protection and transmission lines. This means no interest, land acquisition etc.*
- *Operation and maintenance costs as fixed percentage of total capital costs*

Construction costs
This last assumption results in the fact that only the construction costs will influence the economic feasibility, multiplied with a factor for the operation and maintenance costs. The total costs are consequently a linear function of the construction costs.

5.1.3 Site selection parameters and criteria

As the essential site selection aspects are introduced, the next step is to determine which parameters influence these aspects and these result in a feasibility criterion that a feasible tidal power site should meet.
The relations between site selection aspects, parameters and criteria are illustrated in Figure 5.2. A given site which meets more of the required site selection criteria than other sites will (as a result) be a more promising site for a future tidal power plant.

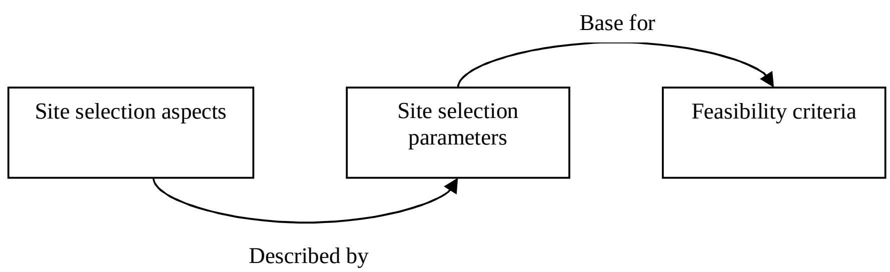


Figure 5.2 Diagram describing relations

The site selection parameters which will be derived, taking into account the subjects determined in the preceding sections, are being illustrated in the next figure. The figure describes the study approach for the final Generic Site Selection Guideline.

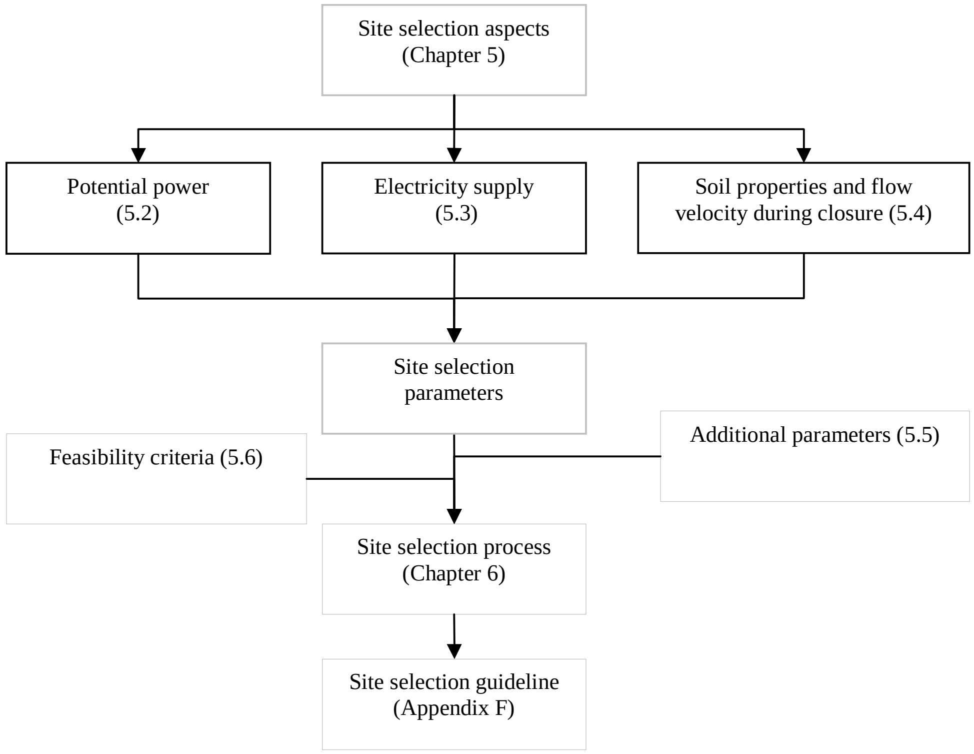


Figure 5.3 Diagram showing study approach

For each of these aspects it will have to be determined whether they will be influenced by one or more parameters and how large the parameter influence will be. With the help of these parameters it would be possible to draw up the possible site selection criteria. Hopefully, in this process, only site specific parameters will be of importance and not the more specific plant design parameters.

5.2 Potential power

One of the most important aspects for a (tidal) power project is the quantity of possible generated power, its potential power, which differs for each site. In literature potential power sometimes is indicated by 'ideal power', as the potential power is the ideal average power generation over a tidal period.
This site characteristic can be roughly estimated without any required operational information such as the power generation scheme, but for a more accurate estimation these schemes are necessary. In the next chapter the amount of energy which could be generated for the varying power generation schemes (One-way or Two-way generation) will be discussed more specifically.
Potential power can be described by an equation, which is built up by site specific parameters. From this, it can be determined which parameters and in what way they will influence the potential power for a site.

5.2.1 Potential power derivation

Potential power is potential average power generation per tidal period and is a site characteristic.

The potential power for a given site can be formulated by deriving the energy volume W in the basin. The energy volume W is the amount of energy in the basin created by the tidal movement and can be derived according to formula 5-1. Here, it is clear that the position shift of the mass centre of the tidal basin s_{mc}, the basin surface area at the mass centre and the basin water level range R_{bas} are important site specific parameters.

$$W = s_{mc} \cdot \rho \cdot g \cdot A_{bas,mc} \cdot R \cdot 10^{-6} \cdot \tfrac{1}{3600} \quad \text{(MWh)} \tag{5-1}$$

Where,

s_{mc}	= mass centre shift, in meters (m)
g	= gravitational acceleration, assumed to be a constant equal to 9.81 m/s^2
ρ	= water density, in kilograms per cubic meter (kg/m^3)
$A_{bas,mc}$	= basin surface area, in square meters (m^2)
R	= average tidal range (MHW-MLW), in meters (m)

By dividing by the tidal period the potential power P_{pot} (in MW) can be defined.

$$\boxed{P_{pot} = \frac{s_{mc} \cdot \rho \cdot g \cdot A_{bas,mc} \cdot R}{10^6 \cdot T} \quad \text{(MW)}} \tag{5-2}$$

Where,

T	= tidal period (for a semidiurnal tide; 12.42 hours = 44712 s), in seconds (s)

To determine the potential power it will be necessary to specify variable site parameters presented in formula 5-2, which are:

- Position shift of the mass centre of the tidal basin s_{mc}
- Basin surface area at basin mass centre $A_{bas,mc}$

In the next subsections these parameters will be worked out, starting with the simplest model (rectangular basin model) and stepwise increasing the complexity of the model.

5.2.2 Rectangular basin

The rectangular basin can be schematized by two rectangular basin cross sections. This is illustrated by Figure 5.4.

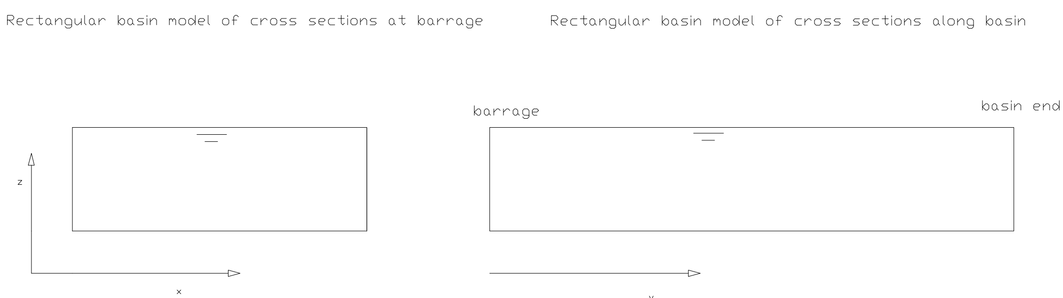


Figure 5.4 Rectangular model for basin volume

The basin level will be equal to the water level outside the basin (sea level), with the same (tidal) range. This can be illustrated by Figure 5.5.

Because the basin surface area of the rectangular shaped basin remains the same over the water depth, the surface area at the mass centre $A_{bas,mc}$ is equal to the surface area at mean seal level $A_{bas,0}$.

From Figure 5.5 can be derived that the weight of the tidal prism will be equal to $\rho g A_0 R$ and the position shift of the mass centre of the tidal basin s_{mc} will be logically half of the basin level range, thus ½R.

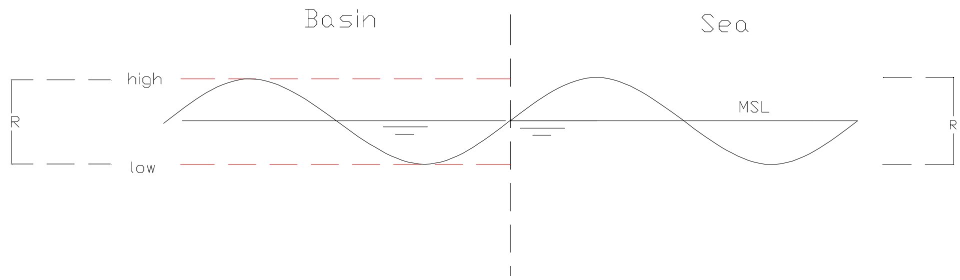


Figure 5.5 Schematization basin level – sea level

Because g = 9.81 m/s^2 and ρ 1027 kg/m^3 (Stuart, 2002), they have no further affect on the potential power for a given site. This results in three remaining parameters $A_{bas,0}$, R, and T for the rectangular basin model, see formula below:

$$P_{pot,rect} = \frac{\rho \cdot g \cdot A_{bas,0} \cdot R^2}{2 \cdot 10^6 \cdot T} \rightarrow P_{pot,rect} = \frac{5037 \cdot A_{bas,0} \cdot R^2}{10^6 \cdot T} \quad \text{(MW)} \qquad (5\text{-}3)$$

Where,
$A_{bas,0}$ = Basin surface area at MSL, in square meters (m^2)
5037 = 0.5*ρ* g, (kg/s^{2}m^2)

5.2.3 Application for varying basin shapes and various generation modes

To generate a more realistic model, it will be necessary to determine the potential power for different basin shapes other than the rectangular model just described. The application for varying basin shapes will however have to be combined with the different generation modes, as will be elaborated later on.

The rectangular basin model assumed that the basin cross sections had a rectangular shape. In reality however, this model will not be representative for sites around the world, where an infinite number of basin shape possibilities can be found. In Figure 5.6 two examples are given to show possible differences in comparison with the rectangular basin shape.

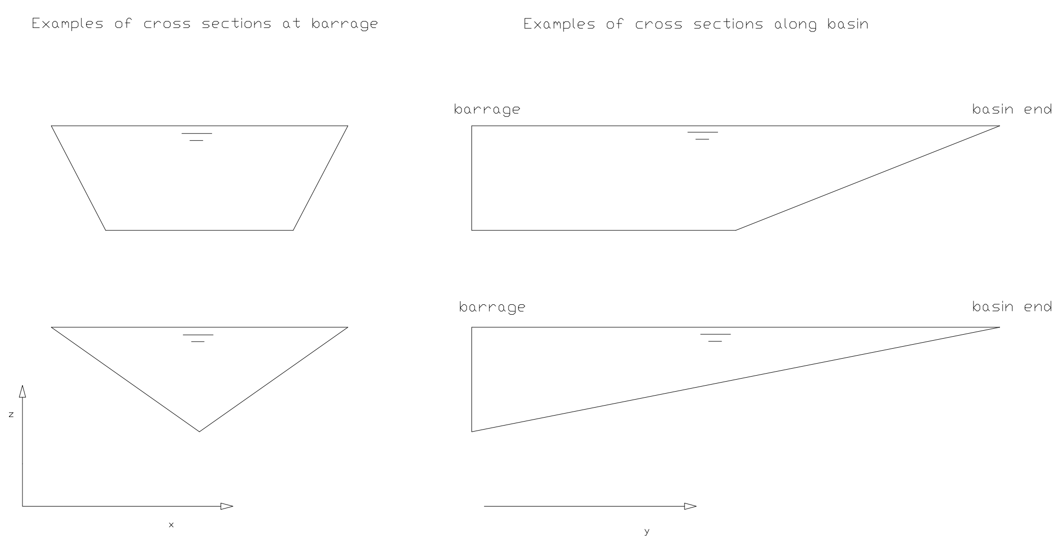


Figure 5.6 Examples basin shapes (trapezoidal and triangular)

The basin cross section shape determines the change of basin surface area by water level change, which has finally effect on the potential power.

As described in formula 5-2 one of the important factors for the potential power is the basin surface area at the mass centre $A_{bas,mc}$. Because each basin has its own shape, this $A_{bas,mc}$ would differ for each separate case.

The surface area at mean high water level in the basin $A_{bas,MHW}$ and the surface area at mean sea level A_0 are easy to measure. This in combination with the mean basin level per operation mode (formula 5-4) makes it possible to come to the shape parameter λ (formula 5-5) and thus the basin surface area related to this λ (formula 5-6).

Several attempts were done to make a model being able to include all these different basin shapes. However, this model would have become too complex for this site selection phase. As a result the following simplification was made:

$$A_{bas,mc} = A_{bas,mean,scheme} \qquad (5\text{-}4)$$

Where,
$A_{bas,mean,scheme}$ = scheme related basin surface area at mean basin level, in square meters (m^2)

This means that the basin surface area at the mass centre will be equal to the basin surface at mean basin level.
For each case the variations in basin shape for the xz-plane as the yz-plane will be taken into account.

The upper-bound basin shape scenario (triangular in both cross sections) is shown in the lower picture of previous Figure 5.6; more specific information on this extreme upper-bound scenario is given in the figure below:

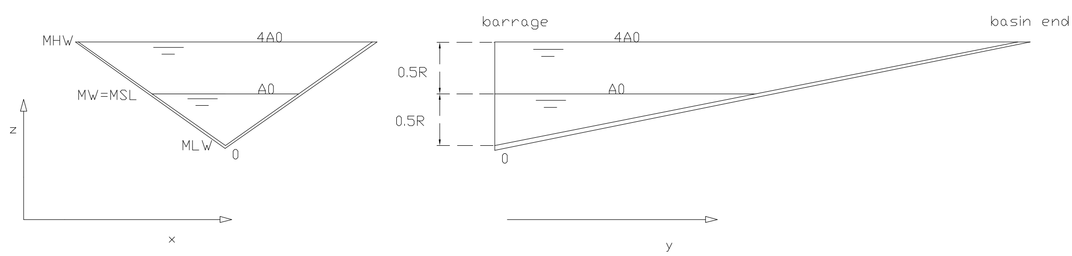


Figure 5.7 Upper-bound basin shape scenario

To define the shape of the tidal basin in combination with the mode of operation, the basin shape parameter λ will be introduced. The derivation of this parameter is to be found in Appendix B2.

$$\lambda = \left(\frac{R + H_{bas,mean,scheme}}{R}\right)^{\sqrt{\frac{4 \cdot A_{bas,MHW}}{3 \cdot A_{bas,0}} - \frac{4}{3}}} \quad (-) \qquad (5\text{-}5)$$

$$A_{bas,mean,scheme} = \lambda \cdot A_{bas,0} \quad (\mathrm{m}^2) \qquad (5\text{-}6)$$

Where,
λ = dimensionless basin shape parameter (-)
$H_{bas,mean,scheme}$ = Scheme related mean basin depth, in meters (m)
$A_{bas,HMW}$ = Basin surface area at MHW, in meters (m)

Now that the basin level ranges for the possible generation modes are known, it is possible to make the next figure for the upper-bound basin scenario:

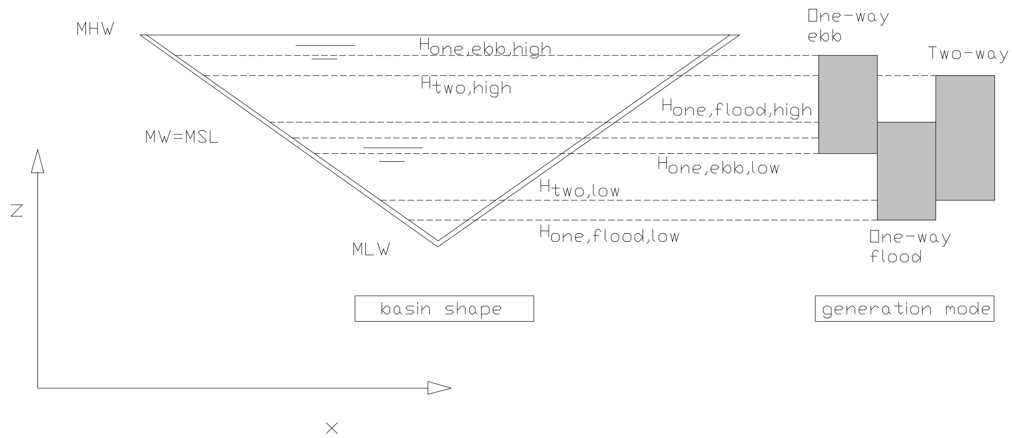


Figure 5.8 Upper-bound basin shape scenario in combination with generation mode

The different basin shapes and related scheme parameter λ are listed in Table 5.2:

Table 5.1 Range of possible basin shape parameters per generation mode

	One-way ebb generation	One-way flood generation	Two-way generation
Rectangular basin	λ=1	λ=1	λ=1
Upper-bound basin	λ=1.32	λ=0.72	λ=1.08

With the information from Table 5.1 the following conclusion can be drawn:

λ = (0.72..1.32) (-)

5.2.4 Results

All the required parameters are now available to estimate the potential power for each site and for each scheme.
This results in the following equations:

$$P_{pot} = \frac{5037 \cdot \lambda \cdot A_{bas,0} \cdot R^2}{10^6 \cdot T} \quad \text{(MW)} \tag{5-7}$$

To be able to compare the potential power for different generation modes, the dimensionless power output parameter β will be introduced, with β_{pot} for the potential power.

Say $$\beta_{pot} = 5037 \cdot \lambda \quad (-) \tag{5-8}$$

Then $$P_{pot} = \frac{\beta_{pot} \cdot A_{bas,0} \cdot R^2}{10^6 \cdot T} \quad \text{(MW)} \tag{5-9}$$

This makes it possible to compare the potential power output parameter β_{pot} for the different generation schemes, see table below.

Table 5.2 Potential power output parameters for different modes of operation

	One-way ebb generation	One-way flood generation	Two-way generation
Rectangular basin Upper-bound basin	$\beta_{pot} = 5.0*10^3$ $\beta_{pot} = 6.6*10^3$	$\beta_{pot} = 5.0*10^3$ $\beta_{pot} = 3.6*10^3$	$\beta_{pot} = 5.0*10^3$ $\beta_{pot} = 5.4*10^3$

The value range can be illustrated by the following graph:

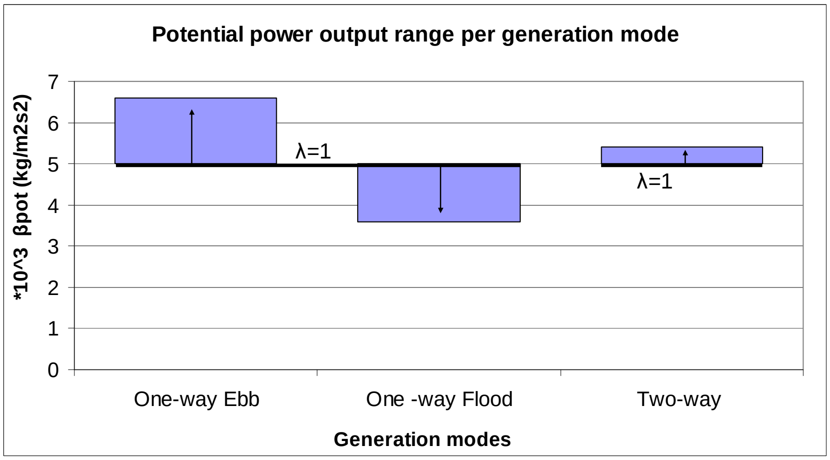


Figure 5.9 Potential power output parameter range per generation mode.

The potential power output parameter clearly shows the same starting level for the simplified rectangular basin (λ=1) for each mode of operation. The effect of a varying basin shape is largest for One-way generation with a positive effect for the ebb generation part and negative for the flood generation part.
The main conclusions which can be drawn from Figure 5.9 are:

- **The shape of the basin has a large influence on the potential power for One-way generation, One-way ebb generation is most favourable for the upper-bound basin shape**
- **For the Two-way generation mode the shape of the basin is almost irrelevant for the potential power output compared to the effect on One-way generation**

Note that from Figure 5.9 can **not** be concluded that:

- **One-way ebb generation scheme generates the largest amount of power**

This is because potential power describes the attractiveness of a site for tidal power in general, not specific per generation mode. Figure 5.9 illustrated only the effect of the basin shape on the different generation modes, influencing the attractiveness of each generation mode.

The real mean power output per generation mode is shown in Appendix A6 and has been used in comparison with the results from the DTP Model. As the real power output will not be taken into account in the site selection process, only the result from this appendix will be stated:
Two-way generation is the best alternative according to the model with a 19% higher power output over a tidal period compared to One-way generation.

5.3 Electricity supply

Section 3.5 briefly introduced the effect of a tidal power plant located far from an electricity grid. But much more electricity generation aspects are involved.

5.3.1 Customer load in combination with tidal energy

As the function of a tidal power plant is to produce power, the plant capacity will have to be determined. But before introducing aspects like capacity, first the extern demand and the properties of tidal power will be discussed.

Demand

Load is the consumed amount of power (in MW), which follows a certain trend over a day with a higher required power level between 8h00 and 20h00. In what follows, a typical load for one day in the Netherlands in 1997 (SEP, 1998) will be applied, making it possible to compare demand with supply.
For all practical purposes a similar distributed load can be assumed for other areas around the world.

Tidal energy properties

As tidal energy fluctuates with the tidal movement, supply varies with the customer demand, which is the major concern for tidal power. The Figures 5.10 and 5.11 show the power generation distribution with respect to the water level inside the basin.

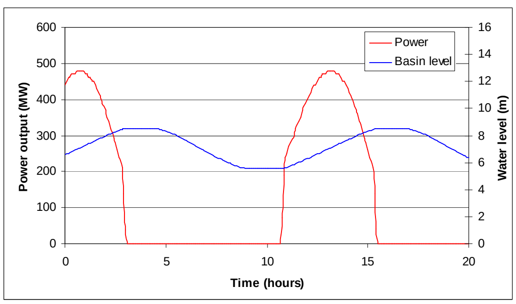


Figure 5.10 Example One-way generation power Output (case 4)

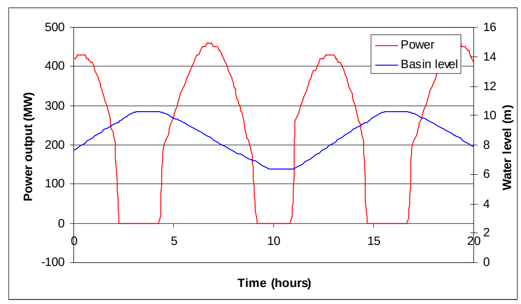


Figure 5.11 Example Two-way generation power output (case 4)

The power supply with respect to the power demand (SEP, 1998) is shown in the figures below.

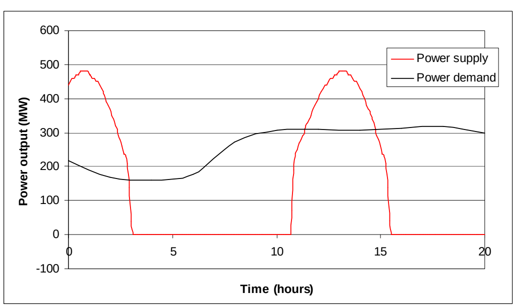


Figure 5.12 Example One-way generation power output (case 4)

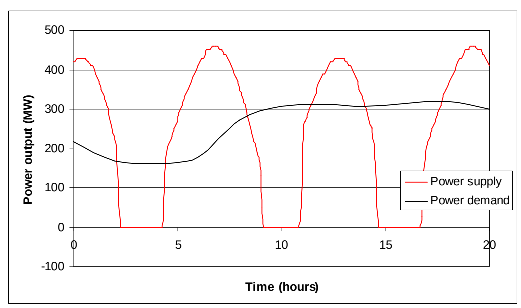


Figure 5.13 Example Two-way generation power output (case 4)

5.3.2 Storage, additional electricity sources and delivery

Storage

Electricity surplus will be assumed to be delivered to this grid without further complication, just as a shortage will be compensated by other power plant connected to the grid.

Storage will only be required on sites without an electricity grid nearby, because here generation shortage, when demand is higher than produced power, will occur. The electricity surplus will be stored and used in a period of shortage. Hence, a storage method is simultaneously a temporarily replaceable electricity source. This means that the difference in rated power of a plant and the highest customer demand over a day should be large enough to be able to store a sufficient amount of electricity.

Main storage possibilities are:

- Pumped storage systems
- Battery systems
- Hydrogen

A pump storage system is another alternative to store and produce electricity by pumping and turbining water between reservoirs at different elevations. The larger the elevation difference, the more electricity can be produced, which means that at least a hilly location is highly preferred.

Application of a battery system, such as modern zinc air or a traditional battery system, is a viable way of storing electricity. It is however a very expensive alternative with a relatively short life expectancy (Hydro Tasmania, 2001).

Hydrogen is a high energy fuel with very low density. By freezing it will be possible to achieve smaller storage volumes, but will lower the efficiency substantially (<25%) (Hydro Tasmania, 2001).

Additional power sources
Besides storage alternatives combined with the generation of electricity, as discussed above, it is also optional to place an additional power source without storage possibilities. This means the rated power can be put on the same level as the highest customer demand over a day.
Most logical power source to be added will be a diesel power station, which could easily bridge the periods of electricity deficiency. This is especially attractive for relatively small power plants.

Delivery
If a site is located near a grid, it just needs to connect the plant to this grid without speaking of the delivery of electricity.
Delivery, as storage, will be a crucial aspect when no grid is nearby and its capacity is larger than the local customer load. Under these circumstances it will be possible to transport electricity or to transport hydrogen (see storage). The transport of electricity will take place by transmission lines in or above the ground. Hydrogen could be transported in a liquid state (by ships) or a gasiform state (by pipelines).
The distance s_{grid} between site and grid will have to be included in the site selection guideline. The quality of this distance on the other hand, such as a transport over rough inhospitable districts or for example over water, will be outside the scope of this thesis and consequently not taken into account.

As it will be more acceptable to cross a certain distance for a giant power project in comparison with a small project, the relation between this distance and the potential power will be introduced as a valuable additional parameter; the grid distance parameter r_{grid}.

$$r_{grid} = \frac{s_{grid}}{P_{pot} \cdot 10^3} \quad \text{(km/MW)} \tag{5-10}$$

5.3.3 Conclusion

Because several storage and delivery options are available, there will always be a suitable variant for each site.
The distance to the grid will be of influence on the site attractiveness and for that reason the grid distance parameter r_{grid} is introduced. The lower the r_{grid}, the more promising the site is. For the moment, no information is available to give a reliable indication on the feasibility boundary condition for this parameter. This parameter makes a valuable comparison possible between different site locations.

5.4 Soil properties and flow velocities during closure

In this section the influence of the soil properties and flow velocity as function of the technical feasibility, such as stability and construction ability, will be handled.

Soil properties

Soil properties could be of influence on the construction stability (regarding the foundation) and on aspects with respect to erosion.
Stability and seepage aspects are assumed not to be an issue as technical possibilities nowadays make it possible to construct on each type of subsoil with the help of certain measures.
Erosion on the other hand has to be taken into account, which can occur during:

- Construction, at the final part of the closure
- Operation, at the entrance and outlet of the turbines and sluice gates

Protecting the subsoil from eroding has already been worked out in section 3.4 for the operational process, where granular material was proposed. As the barrage opening surface area during closure will be at least larger than the opening area during operation and the final closure gap will be closed with caissons, it will be possible to protect the subsoil from eroding during closure.
Besides the bed protection during operation, no additional costs will be taken into account for the bed protection during closure.

Flow velocities during closure

A method to determine the occurring flow velocities during operation has already been introduced in section 3.4 with respect to bed prottection.
High flow velocities during construction could have impact on the construction method. Even when flow velocities during closure are high, above the critical operation flow velocity of about 2 m/s [9] (d'Angremond and van Roode, 2001), this will not make a site non-feasible. Therefore it will not have further impact on the site selection guideline.
For illustration purposes, Appendix B5 shows the method how to derive the flow velocities and water level changes during closure. This will clearly show the decreasing basin range R_{bas}, the increasing phase difference and the fact that larger tidal ranges will go together with higher flow velocities during closure. Therefore, the last section of the closure procedure will be suggested to take place during neap tide.

5.5 Additional site selection parameters

The preceding has shown the different site characteristics (site specific parameters) affecting the potential power of a site, the electricity supply and the closure. However, other parameters could easily simplify the search for promising site. Therefore three additional parameters will be presented.

In the following, the depth ratio r_d and the closure length ratio r_l will be introduced. These ratios make it possible to quickly show the attractiveness of a given site. The lower limit of these two ratios will be 0; a higher ratio, means a more promising site (with the value 1 as maximum).
The third parameter, the construction costs per potential power generation r_{costs}, will be introduced to demonstrate the relation between construction costs and power potential.

5.5.1 Depth ratio r_d

A vertical scale ratio related to the tidal range and the water depth would give some additional valuable information as a larger tidal range has a positive effect on potential power generation. On the other hand, the construction costs of the project will also increase for this case, while a smaller water depth decreases the project construction costs. Without looking at the costs for the tidal project, a depth ratio characterised by the mean tidal range divided by the mean water depth at the barrage could well illustrate how promising a potential site is, the larger this ratio the more attractive the site will be (see formula 5-11). The influence of the costs will be dealt with further on.

---

[9] Flow velocities up to 2 m/s cause no problems, increasing the flow velocity will required additional measures

Shallow estuaries with a large tidal range would show a relatively large depth ratio r_d, where small depth ratios are less attractive. The upper boundary (r_d=1) has a mean tidal range R of twice the mean water depth $H_{w,mean}$.
Minimum conditions which are required for a promising site will be elaborated upon at a later stage, when the guideline for site selection will be drawn up. A depth ratio approaching 0 will not have a positive effect on the site potential.

$$r_d = \frac{R}{2 \cdot H_{w,mean}} \qquad r_d = (0..1) \quad (-) \tag{5-11}$$

This has the advantage that for this depth ratio r_d no new parameters have to be introduced, as it will only require extra research at possible sites.

5.5.2 Barrage length ratio r_l

The total barrage length $L_{barrage}$ fulfils an important role in the site selection process and can be described according to:

$$L_{barrage} = L_{dam} + L_p + L_s \quad (m) \tag{5-12}$$

As illustrated by formula C-4, barrage costs are linear proportional to the barrage length.

The most economical solution will be a minimum barrage length that will consist of only the powerhouse length and the sluice length. For large closures, the functionless dam length can be seen as a rest term, only increasing the construction costs.
The impact on the barrage costs of the change in barrage length $L_{barrage}$ is smaller than the change in mean water depth $H_{w,mean}$ (see formula 3-17).
The barrage length itself will not be a valuable site characteristic, as a larger barrage could also be a result of a larger basin area, which enlarges the potential power for a site. A ratio between the barrage length and the basin surface area solves this problem and illustrates the attractiveness of a selected site; the barrage length ratio r_l.:

$$r_l = \frac{L_{barrage}}{\sqrt{A_{bas,0}}} \quad (-) \tag{5-13}$$

A larger barrage length increases the project construction costs, while a smaller basin area decreases the potential power of a site; both having a negative effect on the site and both increasing the barrage length ratio r_l. As a result it can be stated; the shorter the barrage length factor, the more attractive a selected site will be.
In theory this ratio can take all values between zero and a certain upper limit. Zero can be approached in case of an enormous basin area in combination with a minimum barrage length, but in fact will never reach this value.
The upper boundary will be assumed to be reached in case of a ring-dike[10], where the maximum possible barrage length ratio is 3.54 ($=2\pi r / (\pi r^2)^{1/2}$). Therefore, to create an upper limit of 1, the ratio should be divided by 3.54:

$$r_l = \frac{L_{barrage}}{3.54 \cdot \sqrt{A_{bas,0}}} \qquad r_l = (0..1) \quad (-) \tag{5-14}$$

[10] A ring-dike is an offshore circle shaped basin completely surrounded by a barrage, including powerhouse and sluice gates.

The lower boundary of the barrage length ratio will be defined by the minimum length required to place the powerhouse and sluice gates and will therefore never approach zero. Because the number of powerhouses and sluice gates increases with the tidal range, also flow velocities and scouring increases, resulting in a closure gap supposed to be large enough to accommodate the powerhouses and sluice gates. Therefore no other lower limit other than zero is suggested.

5.5.3 Construction costs per potential power generation r_{costs}

In the previous subsections already two ratio parameters are introduced. One describes the ratio between the mean water depth and the tidal range, where the second deals with the ratio between barrage length and basin area.
It would be valuable to be able to compare projects construction costs with the power potential for that location, which could be defined by the construction costs per power potential r_{costs}:

$$r_{\text{costs}} = \frac{C_t}{P_{pot} \cdot 10^3} \qquad r_{costs} = (0..\infty) \qquad (\$/\text{kW}) \tag{5-15}$$

This ratio will be much difficult to define, as it includes the costs of each plant component.
It will not be a surprise that a low r_{costs} factor, which stands for low costs per potential power generation, will result in a more attractive site for a tidal power plant than high values.

Out of the three determined additional parameters, r_{costs} will be the most important ratio as cost per power is the critical characteristic of a tidal power site.

5.6 Site selection criteria

The different modelled generation schemes showed a minimum required head difference h_{req} as result of turbine technical requirements. From this, the required mean tidal range R_{req} can be introduced as site selection criteria which should be met for feasibility purposes. This study showed the h_{req} to be the only site selection criteria for tidal power generation.

Required mean tidal range R_{req}

In section 2.2 all the information was presented making it possible to come to the required tidal range for the most cost efficient tidal power plant. For the different modes of operation a required tidal head h_{req} of $0.28R$ was derived for generation.
Together with the minimum head difference of 2 m for Bulb turbines determined by supplier VA Tech Hydro (Figure 5.14) it will be possible to derive the optimum economic feasibility criterion for tidal power, as the cost efficient optimum was considered:

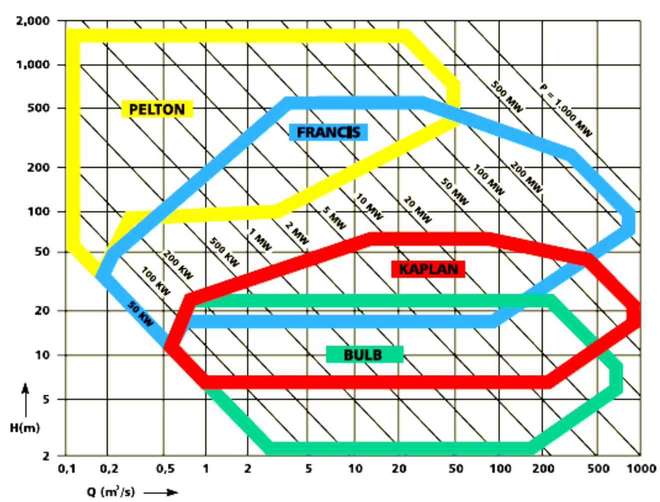


Figure 5.14 Minimum head difference over turbines (VA Tech Hydro)

$$R_{req} = \frac{2}{0.28} = 7.1 \quad (\text{m})$$

This means that a tidal range of about 7 m is required to reach optimal economic feasibility. Technical feasibility, or less favourable economic feasibility, will be reached earlier, but will be less profitable.
If for example a generation head of 0.5*R* was required, a tidal range of 4 meters will already be satisfying, but the project costs will increase per produced unit of energy.

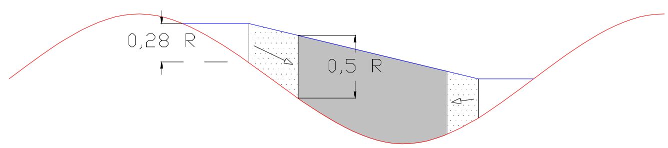


Figure 5.15 Shifting with the required head for generation

Present tidal power studies of literature have shown the following required mean tidal ranges for economic feasibility:

Table 5.3 Required tidal ranges for economic feasibility

Study / Literature	R_{req} (m)
Korean water resources corporation, 2004	5
Schreijgrond et al, 2000	7
E.M. Wilson, 1970	6
Duivendijk, 2004	6

From this section it can be concluded that, if a site does not meet the mean tidal range criterion of 7 m, the site will not reach optimal economic feasibility.

Chapter 6 Site selection process

Now that all the required information for the site selection process is derived, a method will have to be introduced to determine how promising a site is. As each estuary could contain several promising sites, there could be a (large) number of promising sites for a tidal power barrage, demonstrated in the figure below.

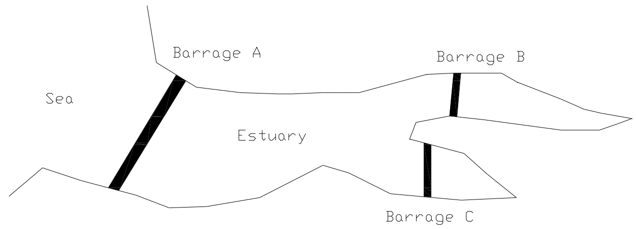


Figure 6.1 Potential sites within an estuary

It will be essential to easily filter the promising estuaries before focusing on details (i.e. costs). The procedures to come to a proper and valuable site selection are shown in the diagram below.

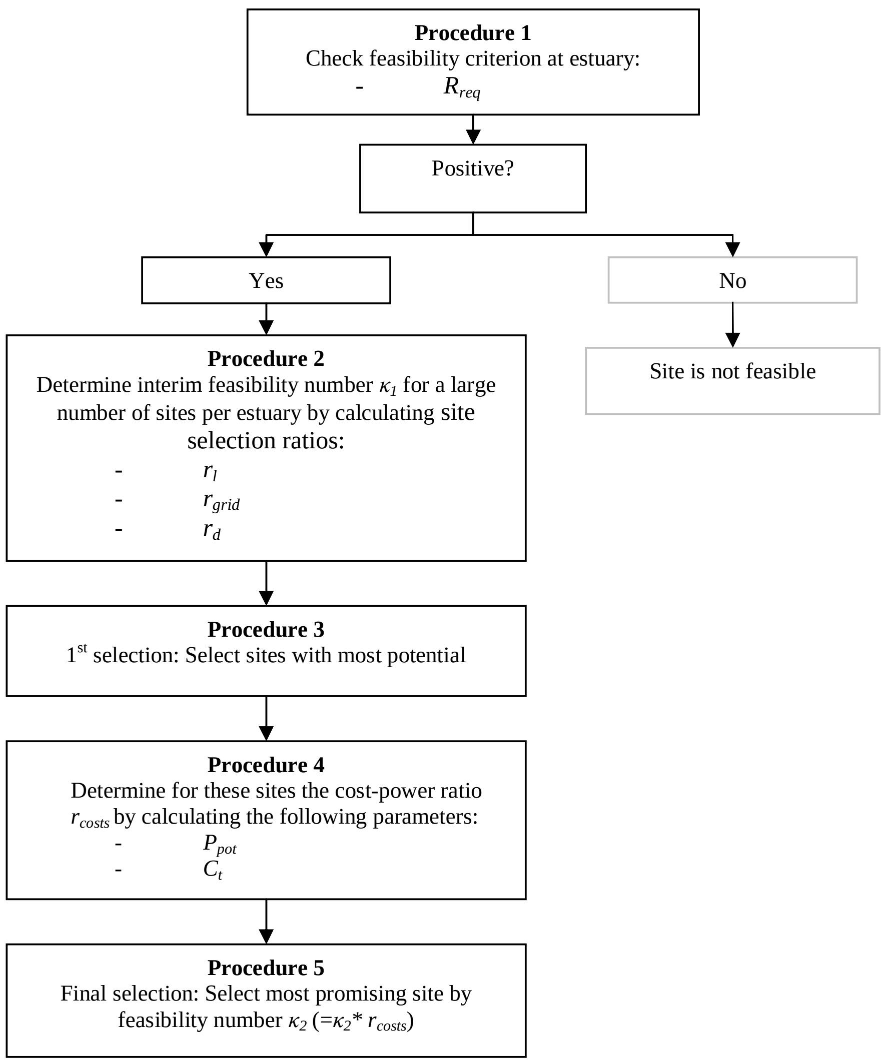


Figure 6.2 Procedure diagram for site selection

As a result, the objective and approach can be determined as follows:

Objective:

- **Determine most potential site**

Approach:

- **Formulate feasibility criterion**
- **Determine interim feasibility number κ_1**
- **Determine feasibility number κ_2**

6.1 Procedure 1: Feasibility criterion

Required mean tidal range (see section 5.6)
In the preceding subsection only one feasibility criterion was required for tidal power, namely the required mean tidal range.

$$R \geq 7 \qquad \text{(m)} \tag{6-1}$$

If parts of an estuary meet this criterion, there are still several possible sites to consider.

6.2 Procedure 2: Interim feasibility number κ_1

This site selection option is another approach to derive the site potential without directly looking at the costs. The three required ratios (r_l ,r_{grid} and r_d) however, are still in an indirect way representing costs; longer barrages (r_l), longer transmission lines (r_{grid}) and deeper waters (r_d) increase the projects expenses. To be able to make a valuable comparison between the different ratios derived in the preceding subsections, equation conversion is required.
A new parameter, the interim feasibility number κ_1, will be introduced which is a summation of these ratios. To come to a valuable conclusion, weight factors should be considered.

6.2.1 Conversion parameter equation

Within this guideline, valuable comparison will be reached when each ratio lies in the range between 0 and 1. When a ratio approaches zero it scores superb, the opposite counts for a ratio of one.
For this method an upper bound scenario for each ratio should be presented. For some ratios this upper boundary will be more difficult to determine than for others, but always in the author's best conscience. While the ratio values can never go below zero, the upper boundary is no hard boundary and can be exceeded for some ratios.

Out of the three ratios discussed, r_l did not require any equation conversion, because it did already meet the comparison criteria.

Barrage length ratio

$$r_l = \frac{L_{barrage}}{3.54 \cdot \sqrt{A_{bas,0}}} \qquad r_l = (0..1) \quad (-) \tag{5-3}$$

Grid distance ratio

Suggested upper bound scenario: 200 km for 100 MW
For Europe the grid is often nearby, but for other countries larger distances are much more common. Present tidal power plants are relatively close to the electricity grid, but several sites and study projects with large tidal ranges are at a far distance from such a grid. The chosen upper limit takes into account these situations.

Conversion was required:

$$r_{grid} = \frac{s_{grid}}{P_{pot} \cdot 10^3} \rightarrow r_{grid} = \frac{s_{grid}}{2 \cdot P_{pot} \cdot 10^3} \qquad r_{grid} \approx (0..1) \qquad \text{(km/MW)} \tag{6-2}$$

Depth ratio

Chosen upper bound scenario: 1 m tidal range for 3 m water depth

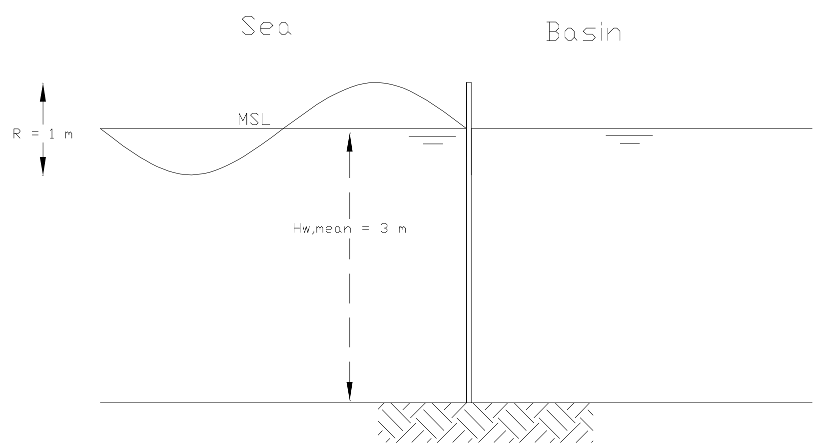


Figure 6.3 Schematisation of chosen upper bound depth ratio

Unnecessarily large water depths increase construction costs. Material volume and thus costs for the barrage dam increases with the square of the depth ($H_{w,mean}^2$). As a result, to fully describe this ratio in combination with the costs, best solution will be to raise the total function to the square.

This results in the following inversion and conversion:

$$r_d = \frac{R}{2 \cdot H_{w,mean}} \Rightarrow r_d = \frac{4 \cdot H_{w,mean}^{\;2}}{R^2} \cdot \frac{1}{36} = \frac{H_{w,mean}^{\;2}}{9 \cdot R^2} \qquad r_d \approx (0..1) \qquad (-) \tag{6-3}$$

6.2.2 Weight factors

To come to a valuable site selection, it is essential to recognize the fact that not all parameters are of the same importance. For that reason, weight factors should be considered.

$$\kappa_1 = wf_{grid} \cdot r_{grid} + wf_d \cdot r_d + wf_l \cdot r_l \qquad (-) \tag{6-4}$$

Where;
wf = dimensionless weight factor (-)

The main parameters from which all three ratios consist (depth, barrage length and transmission distance) are also included in the construction cost ratio r_{costs} (step 4). Therefore, from the economic point of view no difference in weight factor should be considered.

Next to the costs, no well-founded reasons (such as a larger power output) could be determined making it necessary to consider different weight factors. Also, no situation can be drawn for which different weight factors should be applied. Besides, most of the parameter influences are flattened out within the ratio itself, making it unnecessary to define additional weight factors. And for κ_1 , costs are no objective.
Therefore, no weight factors will be considered, resulting in:

$$\kappa_1 = r_{grid} + \cdot r_d + \cdot r_l \qquad \kappa \approx (0..3) \qquad (-) \tag{6-5}$$

All the required information to come to the feasibility number κ_1 is now available. Appendix B6 shows the feasibility numbers for some tidal power sites, where the Mersey barrage and La Rance score better than the Severn barrage.

6.3 Procedure 3: First site selection

The first site selection will filter the most promising site(s) per estuary by using the feasibility number κ_1. Only sites with a certain value of feasibility number κ_1, will be selected for the next step in the site selection process. Which level of κ_1 is acceptable depends on the different derived κ_1 values and will be the customer's choice.

6.4 Procedure 4: Costs per power ratio r_{costs}

The parameter is based on the ratio between the construction costs C_t and the potential power P_{pot}. The lower the ratio, the more promising the site is. In subsection 5.5.3 this ratio is already discussed.

$$r_{\text{costs}} = \frac{C_t}{P_{pot} \cdot 10^3} \qquad r_{costs} = (0..\infty) \qquad (\$/\text{kW}) \tag{5-15}$$

This parameter includes additional financial information compared to the feasibility number κ_1 and will therefore be part of the site selection process.
Subsection 3.1.2 has shown that the total construction costs depend on the type of turbine applied. In section 4.4 a Bulb turbine was suggested for both modes of generation.
For the Generic Site Selection Guideline only Two-way generation in combination with the double regulated Bulb turbine will be applied. This turbine and generation mode choice will not lead to other site preferences.

Unfortunately, r_{costs} can not be compared with the overnight construction costs ($/kW) for other electricity sources which are to be introduced in Chapter 7, because potential power was used and not the installed plant capacity. Whereas mentioned before, potential power is not the same as the installed plant capacity.

6.5 Procedure 5: Final site selection

The second and final site selection will bring the two most important site selection parameters κ_1 and r_{costs} together by multiplication, creating the final feasibility number κ_2:

$$\kappa_2 = \kappa_1 \cdot r_{\text{costs}} \qquad \kappa_2 = (0..\infty) \qquad (-) \tag{6-6}$$

The site with the lowest obtained value can be characterized as the most promising site within the search area.

The resulting Generic Site Selection Guideline can be found in Appendix E.

Chapter 7 Costs of tidal energy

Purpose of this study is to define the feasibility of tidal power generation, where besides technical feasibility, the economical aspect also should be considered.
Imagine a power company planning to construct a new tidal power plant. What are the most important costs and how does these compare with other electricity sources? To answer these questions the position of tidal power in relation to other electricity sources should be determined.
This position will depend on the following three aspects; the overnight construction costs of the project ($/kW), the levelized electricity costs ($cents/kWh) and the capacity factor (-).
Here, the overnight construction costs can be seen as the investment costs, while the levelized electricity costs put the focus more on the production phase. The capacity factor (also called plant factor) is the ratio of the mean power generation to its installed capacity.

According to the Irish energy company Clearpower the overnight construction cost are defined as:
"The capital cost of a project if it could be constructed overnight. This does not include the interest cost of funds used during construction" (Clearpower glossary). These costs should be divided by the plant capacity.
It forms a handy cost reference level because of the fact that cost as well as project size comes together in one condition, which indicates the projects costs prior to the generation phase.

The levelized electricity costs on the other hand represent these additional costs for energy generation, which Clearpower describes as followed:
"The present value of the cost of a resource, including capital, financing and operating costs, expressed as a stream of equal annual payments. This stream of payments can be converted to a unit cost of energy by dividing the annual payment amount by the annual kilowatt-hours produced or saved. By levelizing costs, resources with different lifetimes and generating capabilities can be compared." (Clearpower glossary)

Due the fact that these two aspects represent the costs for two phases which happen in succession, they form two important criteria for an energy company to make a decision between tidal power and other types of electricity generation.

After having derived the most cost efficient plant design, the economic most feasible condition for tidal power can be determined.

The objectives and approach of this chapter will be as follows:

Objectives:
- **Determine costs of tidal energy**
- **Compare tidal energy with other electricity sources**

Approach:
- **Determine overnight construction costs**
- **Determine levelized electricity costs**
- **Determine plant capacity factor**

In this chapter the costs for tidal energy will be determined and compared with other electricity sources. For this, the overnight construction costs for tidal power will be determined in section 7.1, the levelized electricity costs in section 7.2 and the capacity factor in section 7.3. For the other electricity sources these parameters are determined in Appendix C2. The results will be discussed in section 7.4.

7.1 Overnight construction costs

The overnight construction costs can be determined by dividing the total construction costs C_t by the plants capacity $P_{capacity}$. Both are calculated for an ideal tidal power site in Appendix C3 and results in the following:

$$\frac{C_t}{P_{capacity}} = \frac{529 \cdot 10^6}{186 \cdot 10^3} = 2844 \quad (\$/\text{kW}) \tag{7-1}$$

The resulting 2844 $/kW is much higher than the averaged values for other electricity sources, see figure below.

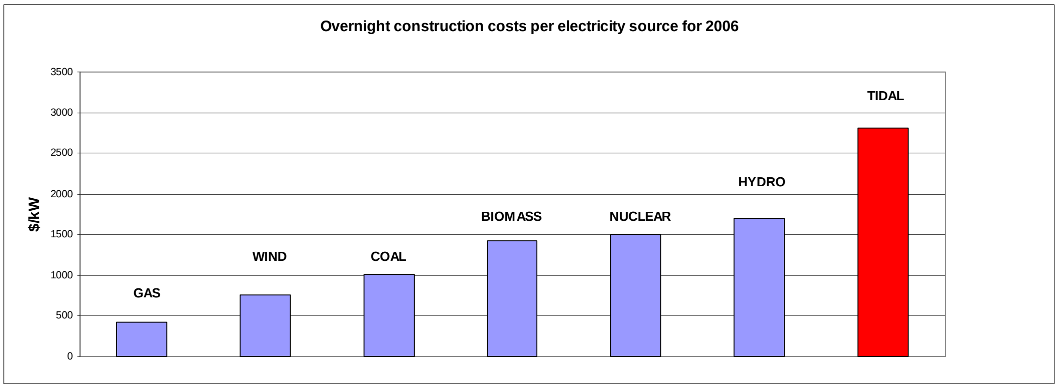


Figure 7.1 Overnight construction costs per electricity source 2006 (see Appendix C2)

For that reason, by just looking at the overnight construction costs, tidal power can not compete with the other electricity sources.

7.2 Levelized electricity costs

The levelized electricity costs are to be calculated by dividing the total costs in a life time $C_{t,life}$ by the total produced energy during this life time E_{life}. The life time was expected to be about 50 years as the La Rance tidal power plant exists already for 40 years and is still operating well.
An operational period of 99 percent was considered as only one turbine will be repaired at the time.

The total construction costs are 529*10^6 $, see Appendix C3.
Operational and maintenance (O&M) costs per year n are considered to be 1 percent[11] of the total costs for the first year. These yearly O&M costs (5.29*10^6 $) should be conversed to present day values (2006) over a period of 50 years. This means that due to the interest rate r the value of the O&M costs decreases, see below.

$$\text{Present day value} = (1 + r/100)^{-n} \tag{7-2}$$

On the other hand, it is likely for the O&M costs to increase during its life time, as more repairs are required and the personnel costs increase. *To avoid uncertainties on interest rates, it is assumed that the decrease in value of the O&M costs is compensated by the increasing O&M costs each year.* This means that the O&M costs per year are 5.29*10^6 $ present day value during its life time, with total O&M costs of 264*10^6 $.

This results in the following levelized electricity costs:

$$\frac{C_t}{P_{t,mean/T} \cdot hours} = \frac{(529 \cdot 10^6 + 264 \cdot 10^6) \cdot 100}{73 \cdot 10^3 \cdot 24 \cdot 365 \cdot 50 \cdot 0.99} = 2.5 \quad (\$\text{c/kWh}) \tag{7-3}$$

[11] For the Severn tidal plant study (Taylor, 2002) and the Swansea tidal power plant (Baker and Leach, 2006) a percentage of 0.5% was applied, but for this study an additional 0.5% for contingencies were taken into account

The resulting 2.5 $c/kWh is lower than the values for other electricity sources, see Figure 7.2.
With this, it is shown that low levelized electricity costs is a attractive advantage of tidal power compared to the other electricity sources.

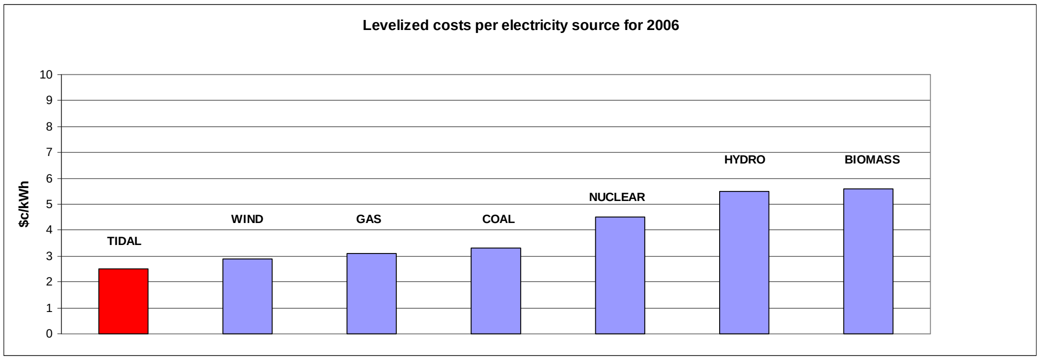


Figure 7.2 Levelized electricity costs per electricity source 2006 (see Appendix C2)

7.3 Capacity factor

The plant capacity factor is the ratio between the mean power output and the installed capacity of the plant and can be derived with the help of Appendix C3:

$$\frac{P_{t,mean}}{P_{capacity}} = \frac{73 \cdot 10^3}{186 \cdot 10^3} = 0.39 \text{ (-)} \qquad (7\text{-}4)$$

The value is about the same as for the other renewable electricity sources as can be seen in the figure below.

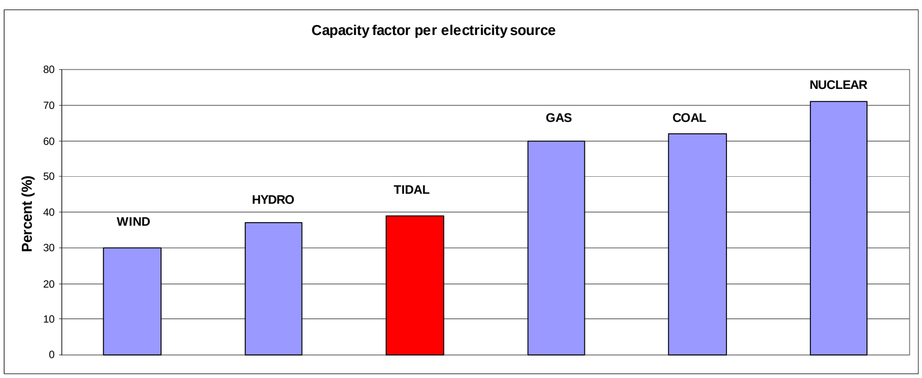


Figure 7.3 Capacity factor per electricity source (see Appendix C2)

7.4 Results

From the previous, it can be concluded that tidal power has very high investment costs (overnight construction costs), even for the economic most attractive plant scenario. The operational and maintenance costs on the other hand are very low, resulting in low levelized electricity costs, which could make tidal power attractive.
The latter is the most essential parameter for economic feasibility as it describes the total costs over a lifetime, instead of just the starting costs.

Because the tidal power values for the overnight construction costs and the levelized electricity costs include several uncertainties (i.e. life time, interest rate and engineering costs) and remains very site specific, no valid conclusions can be drawn on the values it selves.

However, it remains possible to come to valuable conclusions by roughly comparing it with the other electricity sources.

For tidal power, the following conclusions can be drawn:

- **High investments costs**
- **Low generation costs**
- **An average capacity factor, larger than for the other renewable electricity source (wind)**

This meets with the finding from UN-DOALOS, which stated in section 1.1 that the main barrier to increase the use of the tides is that of construction costs.

As a result, tidal power has the potential to compete with other sources. This can be proven by the La Rance tidal power plant, generating at a profitable electricity rate.

A widely used method to indicate energy generation impact on the environment is by determining its external costs. The European Wind Energy Association defines the external costs as follows:
"Such costs represent costs to society that are not paid for by the polluter that cause these emissions."

This indicator would clearly show the environmental friendly aspects of renewable energy, and can therefore be a plus for tidal power. However, as it was impossible to determine or predict the external costs within this tidal power study, no indication of external costs could be made.

Chapter 8 Conclusions and recommendations

8.1 Conclusions

The first part of this report included a plant concept study, analysing the different plant layouts and generation schemes and a general plant and turbine design. The Dynamic Tidal Power Model gave a good insight into the impact of some plant design parameters on the mean power output, finally resulting in the Generic Plant Design Guideline. Main conclusions for the **plant design** were:

- A single basin layout was shown more profitable than a multiple basins layout (>50%);
- For One-way generation the single regulated Bulb turbine was suggested and for Two-way generation the double regulated Bulb turbine;
- Two-way generation is the best alternative according to the DTP Model with at least a 19% energy output compared to One-way generation;
- A smaller amount of large turbines show lower costs and higher efficiencies than a larger amount of small turbines, where a turbine diameter of 5-8 m was proposed;
- The most cost efficient number of turbines is about 75% of the required turbines for maximum power output;
- The level of submergence due to cavitation will only have to be taken into account for small turbines (<2.5m);
- The required head difference for turbining is not a fixed value for each site but varies with the present tidal range. Besides, it is the only way of increasing the mean power output without financial consequences;
- It will be advised to limit the turbine output by the generator capacity (rated power);
- Bed protection at both sides of the turbines and sluice gates might be required during operation;
- Sluice gates are required for One-way generation and suggested for Two-way generation as they increase the mean power output with approximately 10%;
- Pumping is not profitable with normal electricity rates, as it requires more power than it produces, but gains potential when electricity rates (during pumping) are much lower;
- With the Generic Plant Design Guideline it is possible to calculate the essential plant design parameters parameters for an optimum plant design.

In the second part of this thesis the required information to come to a Generic Site Selection Guideline for tidal power barrages was worked out. This study gave a clear view which site specific parameters had influence on the potential power and the projects costs. This resulted in the following conclusions for the **site selection**:

- If a site does not meet the mean tidal range criterion of 7 m, the site can not reach the most economic design for tidal power barrages and will lose attractiveness. Perhaps with other types of turbines, lower mean tidal ranges can be sufficient;
- The cross-sectional shapes of the basin have a large influence on the potential power for One-way generation, in a positive way for the One-way ebb generation mode and negative for One-way flood generation. For the Two-way generation mode the shape of the basin is almost irrelevant for the potential power output;
- The Generic Site Selection Guideline makes it possible to compare different sites on their feasibility, taking into account the site specific parameters but also the economical aspects.

After knowing what it takes to come to an optimum plant design and what define the site potential, it was possible to compare tidal power economical findings with other electricity sources. From this, the following conclusions with respect to its **economic feasibility** could be drawn:

- Tidal power is characterized by high investment costs and low operation and maintenance costs; tidal power has the potential to compete with other electricity sources.

8.2 Recommendations

As a complete plant design was no study objective, more detailed research is required in case it will be an objective. This should include environmental, technical and economical aspects.

With respect to the **environmental** aspects:

- More insight and research is recommended in the possible environmental aspects of tidal power barrages regarding morphology, water level changes and impact on fish habitats.

For the **technical** part of the barrage further investigation is suggested:

- A more detailed powerhouse and sluice gate caisson design, including the selection of the sluice gate type;
- Check the overall stability of the barrage and essential aspects regarding the foundation, taking into account the different loads on the structure;
- The construction phase, including the final closure of the estuary, should be further worked out, by looking at the necessary equipment and the construction period;
- This thesis showed that tidal power in combination with energy storage is possible, but should to be further elaborated. The same counts for the process from generator to the demand area.
- Pumping was shown not to be profitable at constant electricity rates over the day. However, at lower electricity rates (i.e. at night) pumping gains attractiveness. This should be investigated per site.

With respect to the **economic** feasibility of a tidal power plant the following studies are proposed:

- As construction costs and interest rates largely vary over the world, more site specific costs are required;
- As turbine and generator form a large part of the total construction costs, defining the least expensive electromechanical costs by comparing the different suppliers will have a positive influence on the economic feasibility.

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Appendices

List of Content

A Dynamic Tidal Power Model

A1 Introduction

As illustrated in Chapter 3, a dynamical model can be seen as a necessity being able to optimize different plant design parameters.
This DTP Model is a continuation of a model programmed in Delphi by DMC. For a more general use of the model different adjustments and additional functions had to be programmed.

The DTP Model is a numerical model able to calculate water levels, discharges and power output.
Before these calculations can be made, the model requires input data regarding site (site specific parameters) and plant design (plant design parameters).
Site:

- Basin surface area
- Tidal constituents

See Figure A1.

Plant design:

- Turbine and generator characteristics
- Sluice gate characteristics
- Pump characteristics

See Figure A2.

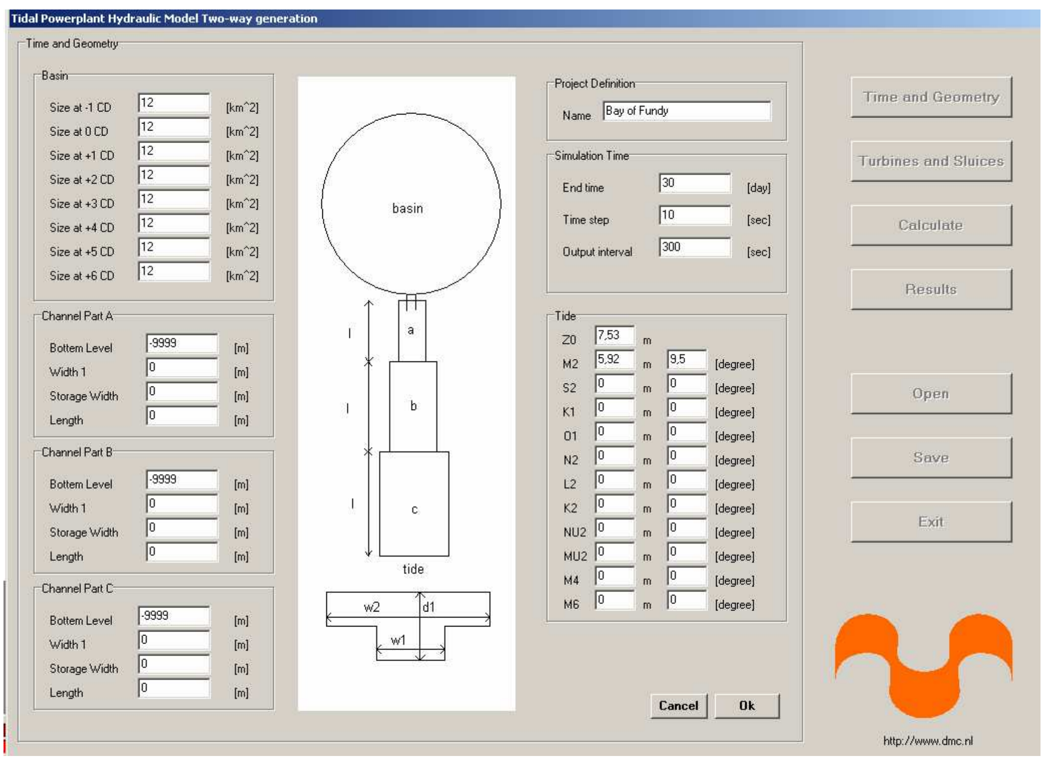


Figure A.1 Input site characteristic

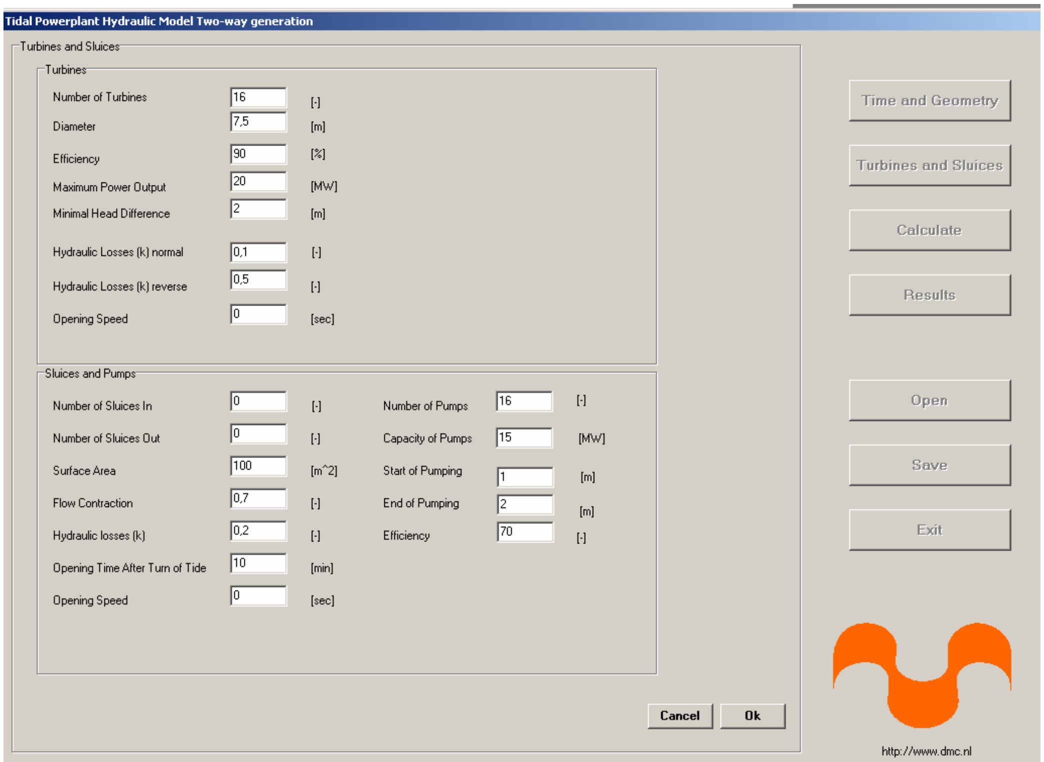


Figure A.2 Input plant design parameters

Two models were required, one for One-way generation and the other for Two-way generation, as they have different operational criteria and conditions. Within the One-way generation mode, it is possible to run Ebb generation as well as a Flood generation.

A2 Applied site cases

Four site cases are worked out to come to an optimum plant design, varying from large basin surface area and tidal range to smaller proportions, see Table A.1. As each case involves a substantial amount of runtime, four cases was sufficient because their optima showed to be closely related to each other.

Table A.1 The four applied site cases

	Case 1	Case 2	Case 3	Case 4
$A_{bas,0}$ (km^2)	12	150	10	75
R (m)	10,84[a]	8	10	6

Each case was exposed to eight different scenarios, with or without sluice gates, upward and downward pumping, see the table below.

Table A.2 The eight applied DTP Model scenarios

Scenarios	1	2	3	4	5	6	7	8
Sluice gates:	×	✓	✓	✓	✓	×	×	×
Pumps downward:	×	×	✓	×	✓	✓	×	✓
Pumps upward:	×	×	×	✓	✓	×	✓	✓

[a] Bay of Fundy (BoF) tide with site specific tidal constituents

A3 Input cases

Case 1: input

One-way generation [flood]

SCENARIOS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
$A_{bas,0}$ (km^2)	12	12	12	12	12	12	12	12
Tide constituents	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide
$N_{turbine}$ (-)	16	16	16	16	16	16	16	16
$D_{turbine}$ (m)	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	1	1	1	1	1	1	1	1
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	0	0	0	0	0	0	0
$N_{s,out}$ (-)	0	20	20	20	20	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	16	16	16	16	16	16
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**0**	**88**	**77**	**83**	**69**	**9**	**1**	**1**

Two-way generation

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	12	12	12	12	12	12	12	12
Tide constituents	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide	BoF tide
$N_{turbine}$ (-)	16	16	16	16	16	16	16	16
$D_{turbine}$ (m)	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5
$\eta_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	20	20	20	20	0	0	0
$N_{s,out}$ (-)	0	20	20	20	20	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
μ (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	16	16	16	16	16	16
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1,5	1,5	0	1,5	1,5
η_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**129**	**144**	**140**	**131**	**127**	**125**	**117**	**112**

Case 2: input

One-way generation
[flood]

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	150	150	150	150	150	150	150	150
Tide constituents (m)	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4
$N_{turbine}$ (-)	40	40	40	40	40	40	40	40
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	1	1	1	1	1	1	1	1
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	0	0	0	0	0	0	0
$N_{s,out}$ (-)	0	40	40	40	40	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	40	40	40	40	40	40
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**0**	**267**	**232**	**228**	**188**	**92**	**66**	**66**

Two-way generation

SCENARIOS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
$A_{bas,0}$ (km^2)	150	150	150	150	150	150	150	150
Tide constituents (m)	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4	h_o=8, a=4
$N_{turbine}$ (-)	40	40	40	40	40	40	40	40
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	40	40	40	40	0	0	0
$N_{s,out}$ (-)	0	40	40	40	40	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	40	40	40	40	40	40
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**259**	**260**	**187**	**227**	**140**	**191**	**235**	**168**

Case 3: input

One-way generation
[flood]

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	10	10	10	10	10	10	10	10
Tide constituents (m)	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5
$N_{turbine}$ (-)	10	10	10	10	10	10	10	10
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	1	1	1	1	1	1	1	1
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	0	0	0	0	0	0	0
$N_{s,out}$ (-)	0	10	10	10	10	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	10	10	10	10	10	10
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**0**	**55**	**52**	**52**	**49**	**9**	**4**	**4**

Two-way generation

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	10	10	10	10	10	10	10	10
Tide constituents (m)	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5	h_o=5, a=5
$N_{turbine}$ (-)	10	10	10	10	10	10	10	10
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	10	10	10	10	0	0	0
$N_{s,out}$ (-)	0	10	10	10	10	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	10	10	10	10	10	40
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**71**	**82**	**80**	**77**	**75**	**68**	**66**	**63**

Case 4: input

One-way generation
[flood]

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	75	75	75	75	75	75	75	75
Tide constituents (m)	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3
$N_{turbine}$ (-)	40	40	40	40	40	40	40	40
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	1	1	1	1	1	1	1	1
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	0	0	0	0	0	0	0
$N_{s,out}$ (-)	0	40	40	40	40	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	40	40	40	40	40	40
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**0**	**144**	**131**	**125**	**27**	**-8**	**-32**	**-32**

Two-way generation

SCENARIOS	1	2	3	4	5	6	7	8
$A_{bas,0}$ (km^2)	75	75	75	75	75	75	75	75
Tide constituents (m)	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3	h_o=8, a=3
$N_{turbine}$ (-)	40	40	40	40	40	40	40	40
$D_{turbine}$ (m)	8	8	8	8	8	8	8	8
$n_{turbine}$ (%)	90	90	90	90	90	90	90	90
P_{rated} (MW)	20	20	20	20	20	20	20	20
h_{min} (m)	2	2	2	2	2	2	2	2
k_{in} (-)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
k_{out} (-)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
s (s)	600	600	600	600	600	600	600	600
$N_{s,in}$ (-)	0	40	40	40	40	0	0	0
$N_{s,out}$ (-)	0	40	40	40	40	0	0	0
A_s (m2)	0	100	100	100	100	0	0	0
mu (-)	0	0,7	0,7	0,7	0,7	0	0	0
k (-)	0	0,2	0,2	0,2	0,2	0	0	0
s (s)	600	600	600	600	600	600	600	600
N_{pump} (-)	0	0	40	40	40	40	40	40
P_{pump} (MW)	0	0	15	15	15	15	15	15
$t_{start,pump}$ (m)	0	0	1	0	1	1	0	1
$t_{end,pump}$ (m)	0	0	0	1	1	0	1	1
n_{pump} (%)	0	0	70	70	70	70	70	70
Mean power output (MW)	**128**	**171**	**148**	**130**	**-36**	**71**	**91**	**49**

A4 Results turbine design parameters

Total turbine surface area ($A_{t,turbine}$)

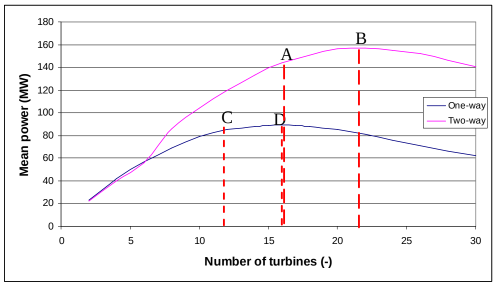


Figure A.3 Turbine number curve Case 1

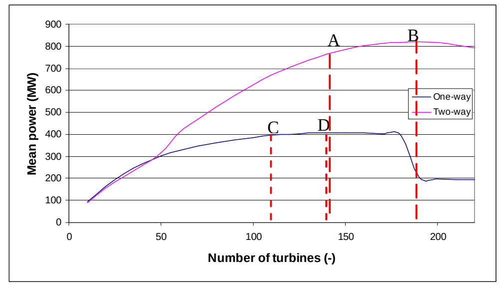


Figure A.4 Turbine number curve Case 2

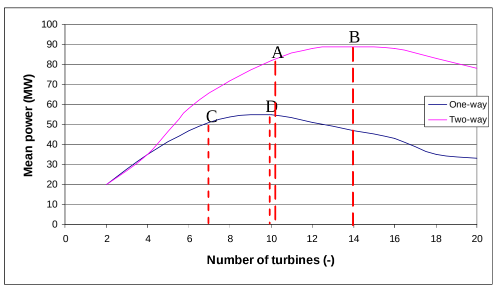


Figure A.5 Turbine number curve Case 3

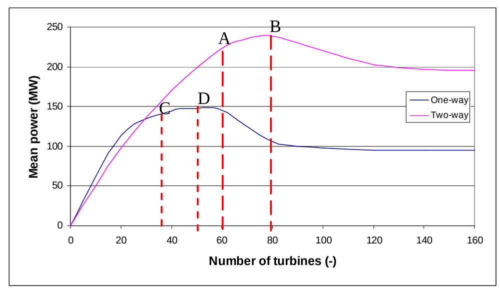


Figure A.6 Turbine number curve Case 4

Table A.3 Turbine surface area summary

		Case 1	Case 2	Case 3	Case 4	
$\frac{A_{bas,o}}{T \cdot \sqrt{2 \cdot g}} \cdot \sqrt{R}$ (m^2)		199	2142	160	927	
Total turbine surface (m^2)						
One-way	C	530	5479	352	1860	
	D	707	7288	503	2513	
Two-way	A	707	7138	503	3016	
	B	972	9550	704	4021	
α_A (-)						**Average**
One-way	C	2.66	2.56	2.20	2.01	**2.4**
	D	3.55	3.40	3.14	2.71	**3.2**
Two-way	A	3.55	3.33	3.14	3.25	**3.3**
	B	4.88	4.46	4.40	4.34	**4.5**

Rated power (P_{rated})

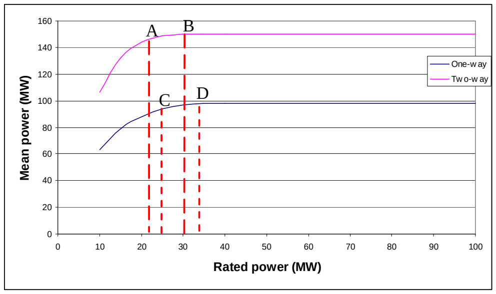


Figure A.7 Rated power curve Case 1

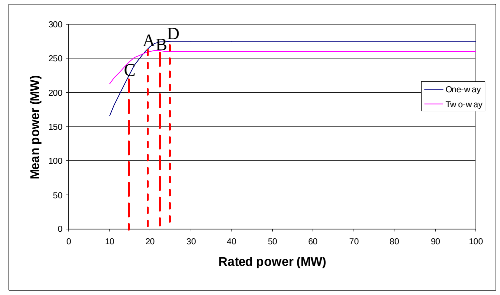


Figure A.8 Rated power curve Case 2

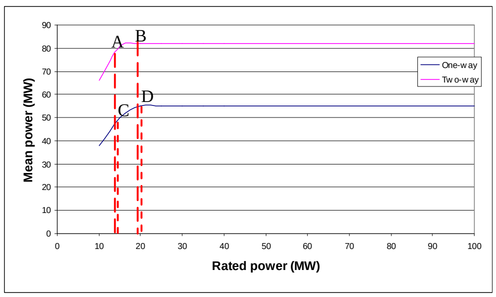


Figure A.9 Rated power curve Case 3

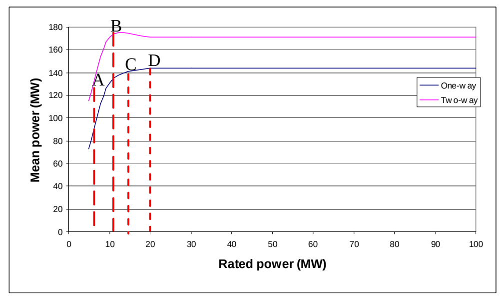


Figure A.10 Rated power curve Case 4

Table A.4 Rated power summary

		Case 1		Case 2		Case 3		Case 4		**Average**
		P_{rated}	h_{rated}	P_{rated}	h_{rated}	P_{rated}	h_{rated}	P_{rated}	h_{rated}	$\boldsymbol{h_{rated}}$
One-way	C	26	0.53R	19	0.54R	15	0.37R	15	0.61R	**0.51*R***
	D	35	0.65R	25	0.64R	20	0.44R	20	0.74R	**0.62*R***
Two-way	A	20	0.48R	15	0.46R	15	0.37R	7	0.37R	**0.42*R***
	B	30	0.59R	20	0.56R	20	0.44R	10	0.46R	**0.51*R***

Required head (h_{req})

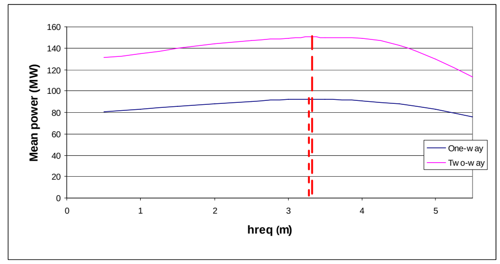


Figure A.11 Minimum required head curve Case 1

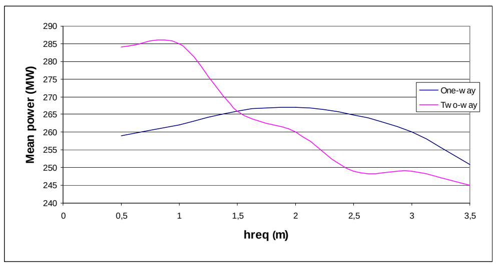


Figure A.12 Minimum required head curve Case 2 (far from optimum design point)

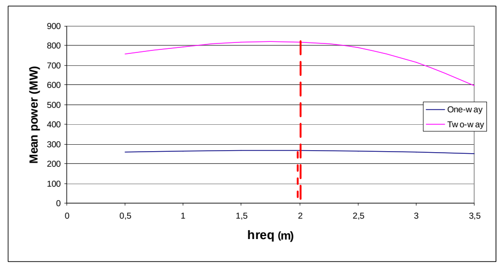


Figure A.13 Minimum required head curve Case 2 (closer to the optimum)

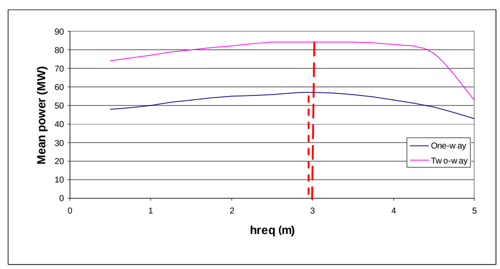


Figure A.14 Minimum required head curve Case 3

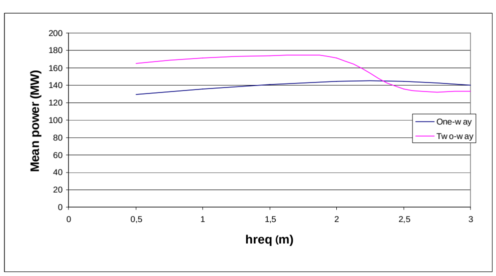


Figure A.15 Minimum required head curve Case 4 (far from optimum design point)

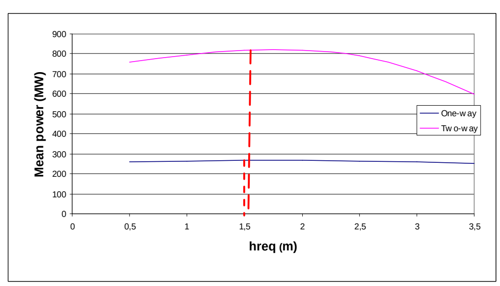


Figure A.16 Minimum required head curve Case 4 (closer to the optimum)

The figures above shows a remarkable difference between the left hand side (starting points for the cases), designed far from the optima, and the right hand side designed near the optimum design points. If the number of turbines and sluice gates are too small, no constant relation can be found between the required head and the mean tidal range (as is illustrated on the left hand side).

For situations closer to the optimum design points, a required head of 0.28*R* results in the largest mean power output, as can be found in Table A.5.

Table A.5 Required head summary

	Case 1	Case 2	Case 3	Case 4	
h_{req} (m)	3.3	2	3	1.5	
R (m)	10.84	8	10	6	
h_{req} (m)	0.30R	0.25R	0.30R	0.25R	**Average: 0.28*R***

Total sluice gate surface area ($A_{t,s}$)

DTP Model implementation
Whether or not the earlier presented sluice gate surface area really is the optimum can hopefully be checked by the model. Further, it will be likely to see a fixed relation between the sluice gate and the turbine surface area as in formula 3-14.
For the sluice gates area a contraction coefficient μ of 0.7 was taken into account.

DTP Model results
For all cases, the model shows a curve where the mean power output increases with the number of sluice gates, until a certain level has been reached where the number of sluices has no further effect on the mean power output.

The positive effect of sluices gates for Two-way generation is illustrated in the figure below. When opening the sluice gates at the end of the turbine period, the basin range will increase. This has a positive effect on the head difference and generation period. The DTP Model has shown that this increases the mean power output with 10%.

This horizontal part of the curve will be reached at an earlier stage for One-way generation than for Two-way generation. The figure describes the necessity of sluices (assuming the turbines do not operated as sluice gates).
The optimum total sluice gate surface area $A_{t,s}$ is the point from where any additional sluice gate will cost more than it brings up.

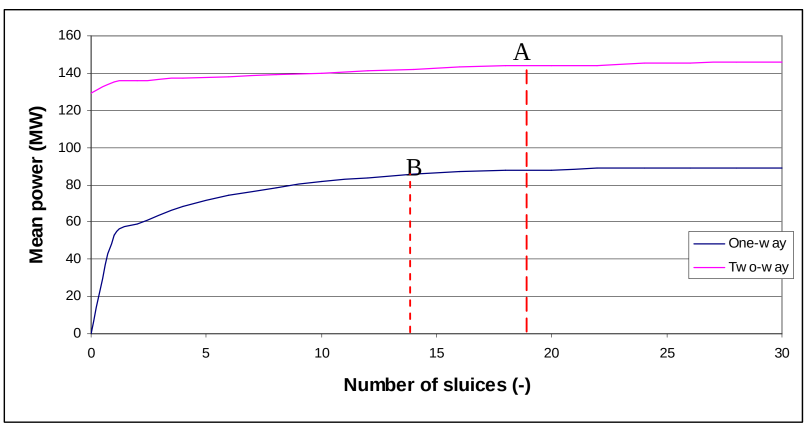


Figure A.17 Example total sluice gate surface area curve

The total sluice gate surface area $A_{t,s}$ does not show a clear optimum like the two preceding parameters ($A_{t,turbine}$ and h_{req}) which follows from the figures below:

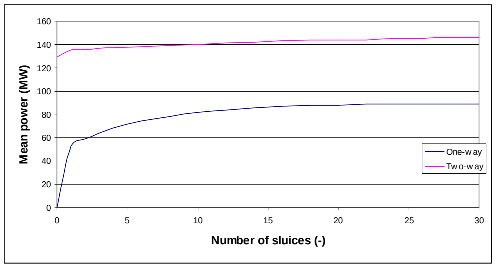


Figure A.18 Sluice gate number curve Case 1

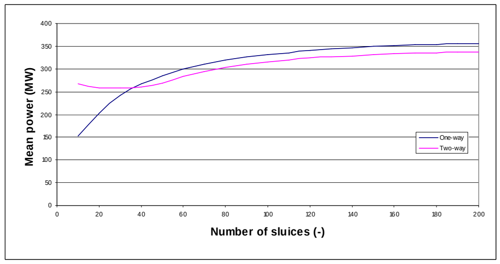


Figure A.19 Sluice gate number curve Case 2 (far from optimum design point)

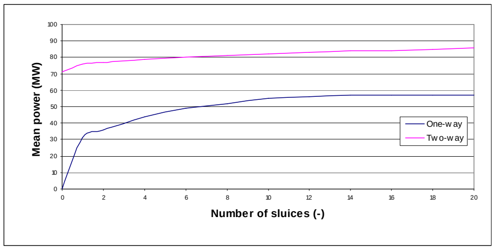


Figure A.20 Sluice gate number curve Case 3

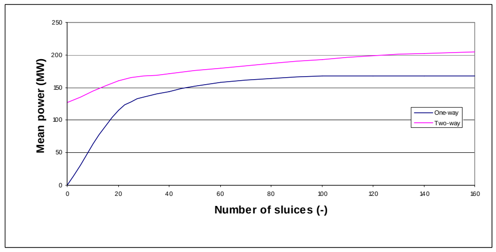


Figure A.21 Sluice gate number curve Case 4

In theory, the curves have to remain horizontal after a while when the sluice gate surface area has reached the point that the basin level is able to follow the sea level (without any head difference). Further increasing the sluice gate surface area will have no effect as no extra mean power output can be generated anymore.
Placing the design point at the start of this horizontal section will not be attractive as the last sluice gate section has little influence on the mean power output. On the other hand, design points at the steepest part of the curve, where the last sluice gate section generated the largest effect on the mean power output, resulted in a mean power output far below the potential.

No visual optimum can be found in the plotted curves below. **Therefore the optimum design point will be assumed to follow the results determined by formula 3-14; $A_{t,s} \approx 2*A_{t,turbine}$**, which seems reasonable by looking at point A and B in the figure. Keeping in mind that sluice gates are much less expensive than turbines, each additional percent of extra power by increasing the number of sluice gates counts.

Pump surface area ($A_{t,pump}$)

For each of the four cases the most potential pumping scenario is worked out. These scenarios were marked in red in the input tables for the different case (A3).

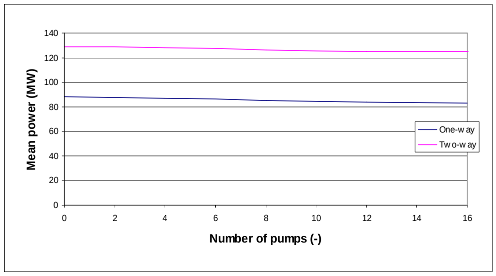


Figure A.22 Pump number curve Case 1

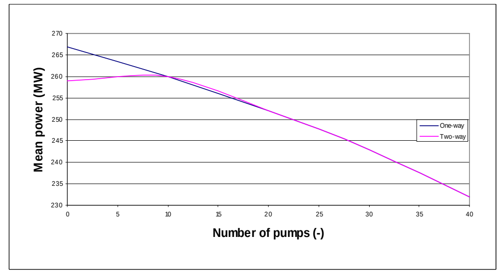


Figure A.23 Pump number curve Case 2 (far from optimum design point)

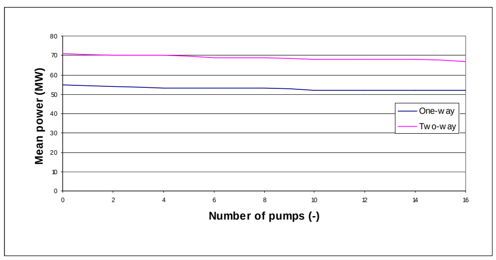


Figure A.24 Pump number curve Case 3

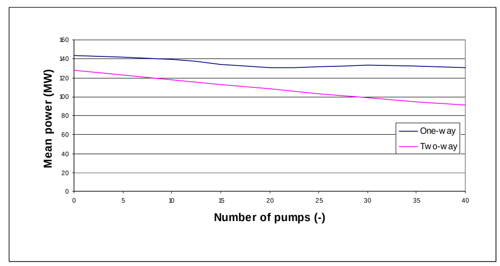


Figure A.25 Pump number curve Case 4

The figures show that without pumps the mean power output is highest, meaning that (with a fixed $h_{start,pump}$ or $h_{end,pump}$) pumping is not effective: **a pump uses more energy than it produces**.
Whether this conclusions remains valid when the fixed $h_{start,pump}$ or $h_{end,pump}$ will vary, is worked out in the next pages.

Starting head for pumping ($h_{start,pump}$)

Varying the starting head for pumping does not suddenly make pumping worthy as can be seen in the figures below.

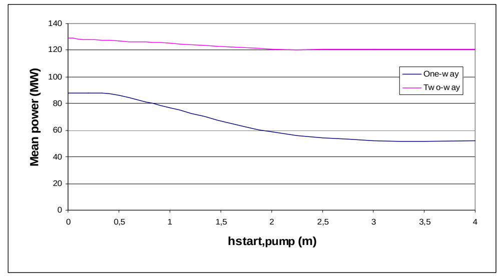


Figure A.26 Starting head for pumping curve Case 1

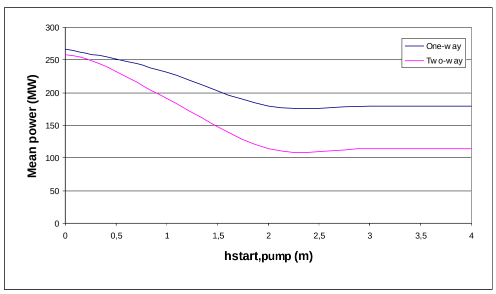


Figure A.27 Starting head for pumping curve Case 2 (far from optimum design point)

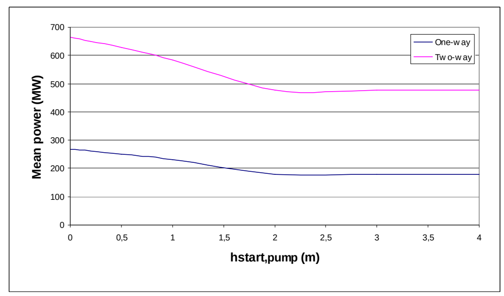


Figure A.28 Starting head for pumping curve Case 2 (closer to the optimum)

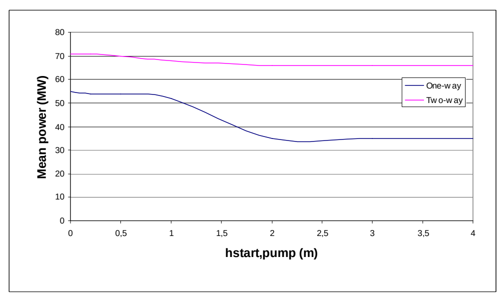


Figure A.29 Starting head for pumping curve Case 3

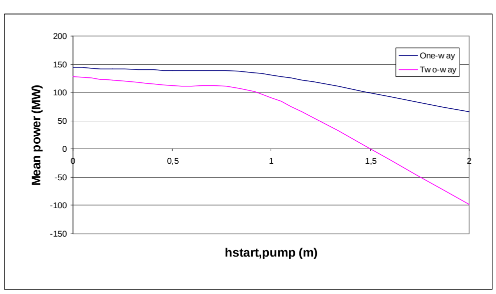


Figure A.30 Starting head for pumping curve Case 4 (far from optimum design point)

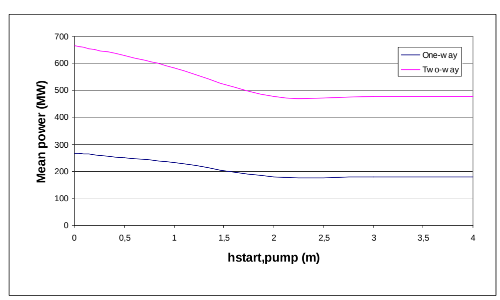


Figure A.31 Starting head for pumping curve Case 4 (closer to the optimum)

End head for pumping ($h_{end,pump}$)

Varying the end head for pumping will also have no effect on the pumping potential, as can be seen in the figures below.

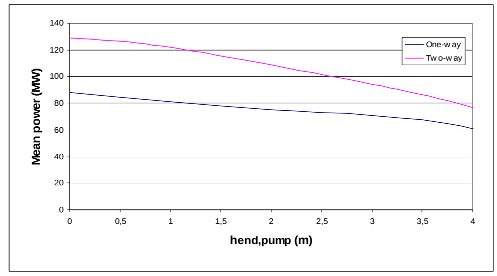


Figure A.32 End head for pumping curve Case 1

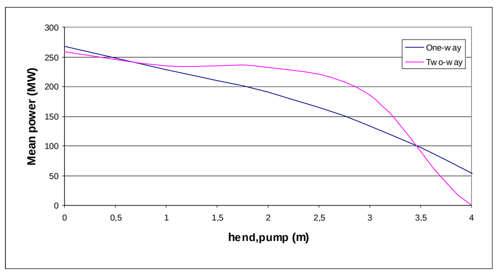


Figure A.33 End head for pumping curve Case 2 (far from optimum design point)

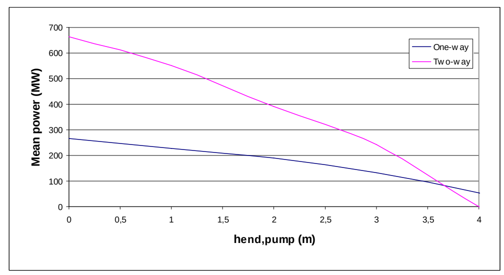


Figure A.34 End head for pumping curve Case 2 (closer to the optimum)

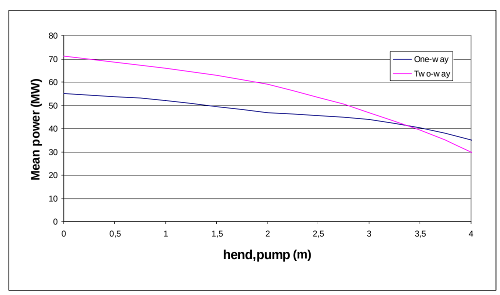


Figure A.35 End head for pumping curve Case 3

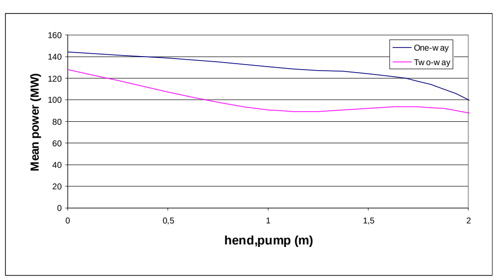


Figure A.36 End head for pumping curve Case 4 (far from optimum design point)

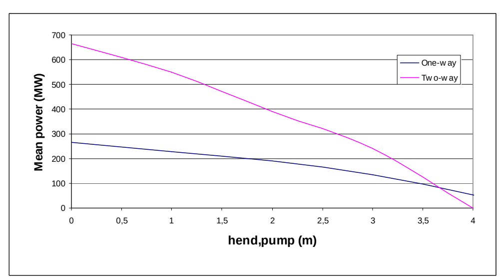


Figure A.37 End head for pumping curve Case 4 (closer to the optimum)

A5 Resulting generation schemes

An example for the model output is illustrated below, from where essential information can be derived making it able to can to the generation schemes.

Time [s]		Tide [m]	Outside Basin [m]	Basin [m]		Q-Turbines [m^3/s]	E-Turbines [w]	Q-Sluices [m^3/s]	Q-Pumps [m^3/s]	E-Pumps [w]
0	0	10,63	10,63	6,51	4,12	45057	1,70E+09	0	0	0,00E+00
300	0,08333	10,76	10,76	6,6	4,16	45245	1,70E+09	0	0	0,00E+00
600	0,16667	10,88	10,88	6,69	4,19	45403	1,70E+09	0	0	0,00E+00
900	0,25	10,99	10,99	6,78	4,21	45531	1,70E+09	0	0	0,00E+00
1200	0,33333	11,1	11,1	6,87	4,23	45629	1,80E+09	0	0	0,00E+00
1500	0,41667	11,21	11,21	6,96	4,25	45697	1,80E+09	0	0	0,00E+00
1800	0,5	11,3	11,3	7,05	4,25	45733	1,80E+09	0	0	0,00E+00
2100	0,58333	11,4	11,4	7,14	4,26	45737	1,80E+09	0	0	0,00E+00
2400	0,66667	11,48	11,48	7,23	4,25	45709	1,80E+09	0	0	0,00E+00
2700	0,75	11,56	11,56	7,33	4,23	45649	1,80E+09	0	0	0,00E+00
3000	0,83333	11,64	11,64	7,42	4,22	45554	1,70E+09	0	0	0,00E+00
3300	0,91667	11,7	11,7	7,51	4,19	45426	1,70E+09	0	0	0,00E+00
3600	1	11,76	11,76	7,6	4,16	45264	1,70E+09	0	0	0,00E+00
3900	1,08333	11,82	11,82	7,69	4,13	45066	1,70E+09	0	0	0,00E+00
4200	1,16667	11,86	11,86	7,78	4,08	44833	1,70E+09	0	0	0,00E+00
4500	1,25	11,9	11,9	7,87	4,03	44563	1,60E+09	0	0	0,00E+00
4800	1,33333	11,94	11,94	7,96	3,98	44257	1,60E+09	0	0	0,00E+00
5100	1,41667	11,96	11,96	8,05	3,91	43912	1,60E+09	0	0	0,00E+00
5400	1,5	11,98	11,98	8,13	3,85	43530	1,50E+09	0	0	0,00E+00
5700	1,58333	11,99	11,99	8,22	3,77	43108	1,50E+09	0	0	0,00E+00
6000	1,66667	12	12	8,31	3,69	42646	1,40E+09	0	0	0,00E+00
6300	1,75	12	12	8,39	3,61	42144	1,40E+09	0	0	0,00E+00
6600	1,83333	11,99	11,99	8,47	3,52	41599	1,30E+09	0	0	0,00E+00
6900	1,91667	11,97	11,97	8,56	3,41	41012	1,30E+09	0	0	0,00E+00
7200	2	11,95	11,95	8,64	3,31	40380	1,20E+09	0	0	0,00E+00
7500	2,08333	11,92	11,92	8,72	3,2	39703	1,20E+09	0	0	0,00E+00
7800	2,16667	11,88	11,88	8,8	3,08	38979	1,10E+09	0	0	0,00E+00
8100	2,25	11,84	11,84	8,87	2,97	38207	1,00E+09	0	0	0,00E+00
8400	2,33333	11,79	11,79	8,95	2,84	37384	9,60E+08	0	0	0,00E+00
8700	2,41667	11,73	11,73	9,02	2,71	36509	9,00E+08	0	0	0,00E+00
9000	2,5	11,66	11,66	9,1	2,56	35579	8,30E+08	0	0	0,00E+00
9300	2,58333	11,59	11,59	9,17	2,42	34592	7,60E+08	0	0	0,00E+00
9600	2,66667	11,52	11,52	9,23	2,29	33543	7,00E+08	0	0	0,00E+00
9900	2,75	11,43	11,43	9,3	2,13	32430	6,30E+08	0	0	0,00E+00
10200	2,83333	11,34	11,34	9,36	1,98	29686	5,30E+08	0	0	0,00E+00
10500	2,91667	11,25	11,25	9,41	1,84	13561	2,30E+08	0	0	0,00E+00
10800	3	11,15	11,15	9,42	1,73	0	0,00E+00	0	0	0,00E+00
11100	3,08333	11,04	11,04	9,42	1,62	0	0,00E+00	0	0	0,00E+00
11400	3,16667	10,93	10,93	9,42	1,51	0	0,00E+00	0	0	0,00E+00
11700	3,25	10,81	10,81	9,42	1,39	0	0,00E+00	0	0	0,00E+00
12000	3,33333	10,69	10,69	9,42	1,27	0	0,00E+00	0	0	0,00E+00
12300	3,41667	10,56	10,56	9,42	1,14	0	0,00E+00	0	0	0,00E+00
12600	3,5	10,43	10,43	9,42	1,01	0	0,00E+00	0	0	0,00E+00
12900	3,58333	10,29	10,29	9,42	0,87	0	0,00E+00	0	0	0,00E+00
13200	3,66667	10,15	10,15	9,42	0,73	0	0,00E+00	0	0	0,00E+00
13500	3,75	10,01	10,01	9,42	0,59	0	0,00E+00	0	0	0,00E+00
13800	3,83333	9,86	9,86	9,42	0,44	0	0,00E+00	0	0	0,00E+00
14100	3,91667	9,71	9,71	9,42	0,29	0	0,00E+00	0	0	0,00E+00
14400	4	9,55	9,55	9,42	0,13	0	0,00E+00	0	0	0,00E+00
14700	4,08333	9,4	9,4	9,42	0,02	0	0,00E+00	-4517	0	0,00E+00
15000	4,16667	9,24	9,24	9,39	0,15	0	0,00E+00	-15349	0	0,00E+00
15300	4,25	9,08	9,08	9,36	0,28	0	0,00E+00	-20770	0	0,00E+00
15600	4,33333	8,91	8,91	9,31	0,4	0	0,00E+00	-24812	0	0,00E+00
15900	4,41667	8,75	8,75	9,26	0,51	0	0,00E+00	-28124	0	0,00E+00
16200	4,5	8,58	8,58	9,2	0,62	0	0,00E+00	-30964	0	0,00E+00
16500	4,58333	8,42	8,42	9,13	0,71	0	0,00E+00	-33464	0	0,00E+00
16800	4,66667	8,25	8,25	9,07	0,82	0	0,00E+00	-35703	0	0,00E+00
17100	4,75	8,08	8,08	8,99	0,91	0	0,00E+00	-37730	0	0,00E+00
17400	4,83333	7,91	7,91	8,91	1	0	0,00E+00	-39580	0	0,00E+00
17700	4,91667	7,74	7,74	8,83	1,09	0	0,00E+00	-41278	0	0,00E+00
18000	5	7,57	7,57	8,75	1,18	0	0,00E+00	-42840	0	0,00E+00

Figure A.38 Example model output for Case 2 with One-way generation

Only the cases 2, 3 and 4 will be used to derive the generation schemes, as for Case 1 too many tidal constituents have been taken into account. The additional sinusoid makes it impossible to come to a general generation scheme.

This output results in the following graph for a period of 20 hours.

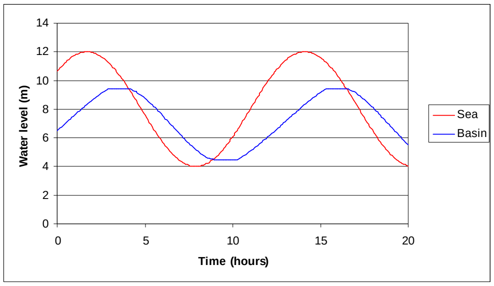


Figure A.39 Water level curve Case 2 (One-way)

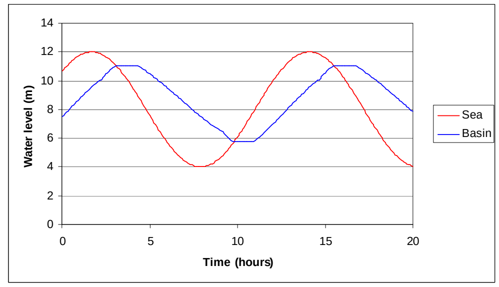


Figure A.40 Water level curve Case 2 (Two-way)

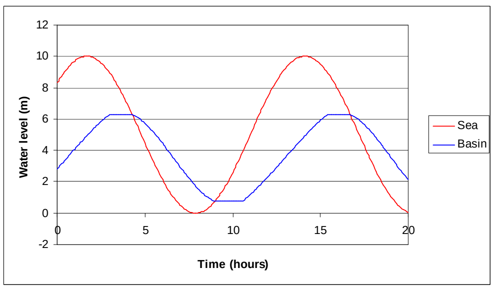


Figure A.41 Water level curve Case 3 (One-way)

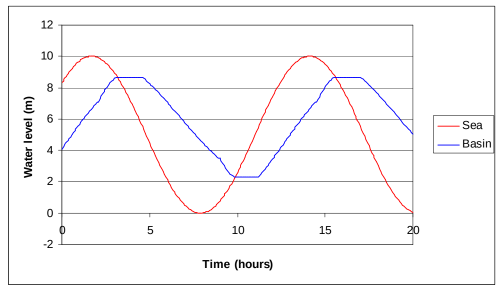


Figure A 42 Water level curve Case 3(Two-way)

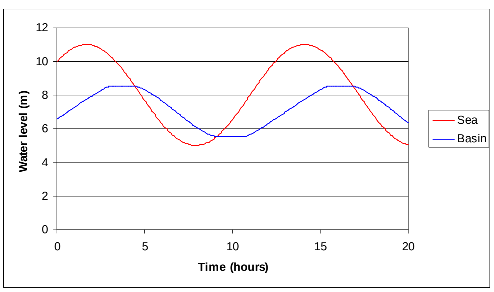


Figure A.43 Water level curve Case 4 (One-way)

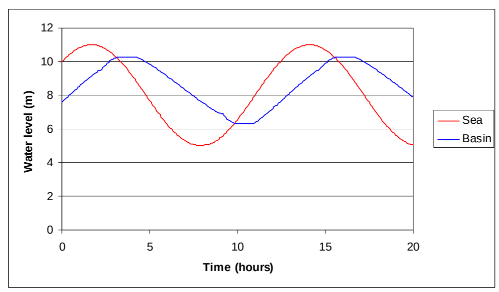


Figure A.44 Water level curve Case 4 (Two-way)

Table A.5 Case results for One-way generation

	h_{mean}	h_{max}	R_{bas}	$T_{generation}$	$H_{bas,high}$	$H_{bas,low}$	$H_{bas,mean}$
Case 2	0.425R	0.531R	0.677R	0.389T	0.500R	-0.177R	0.161R
Case 3	0.468R	0.569R	0.548R	0.376T	0.423R	-0.125R	0.149R
Case 4	0.497R	0.595R	0.497R	0.389T	0.410R	-0.097R	0.156R
Average	**0.46*R***	**0.56*R***	**0.57*R***	**0.38*T***	**0.44*R***	**-0.13*R***	**0.15*R***

For the Two-way generation more effort was required, as it consists of unequal ebb (1) and flood (2) parts which have to be averaged for general application.

Table A.6 Parameters which require averaging for ebb and flood part of Two-way generation

	$h_{mean,1}$	$h_{mean,2}$	$h_{max,1}$	$h_{max,2}$	$T_{generation,1}$	$T_{generation,2}$
Case 2	0.411*R*	0.345*R*	0.507*R*	0.401*R*	0.382*T*	0.295*T*
Case 3	0.443*R*	0.381*R*	0.529*R*	0.426*R*	0.356*T*	0.262*T*
Case 4	0.412*R*	0.346*R*	0.510*R*	0.402*R*	0.382*T*	0.295*T*

Table A.7 Case results for Two-way generation

	h_{mean}	h_{max}	R_{bas}	$T_{generation}$	$H_{bas,high}$	$H_{bas,low}$	$H_{bas,mean}$
Case 2	0.378*R*	0.454*R*	0.655*R*	0.339*T*	0.375*R*	-0.280*R*	0.047*R*
Case 3	0.412*R*	0.477*R*	0.639*R*	0.309*T*	0.367*R*	-0.272*R*	0.047*R*
Case 4	0.379*R*	0.456*R*	0.650*R*	0.339*T*	0.373*R*	-0.277*R*	0.048*R*
Average	**0.39*R***	**0.56*R***	**0.57*R***	**0.33*T***	**0.37*R***	**-0.28*R***	**0.05*R***

This result in the following three schemes:

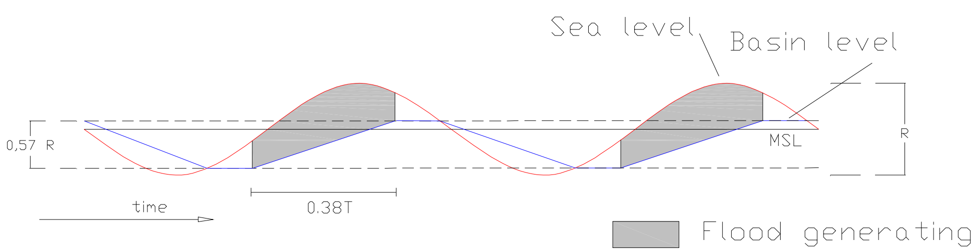


Figure A.45 One-way ebb generation scheme

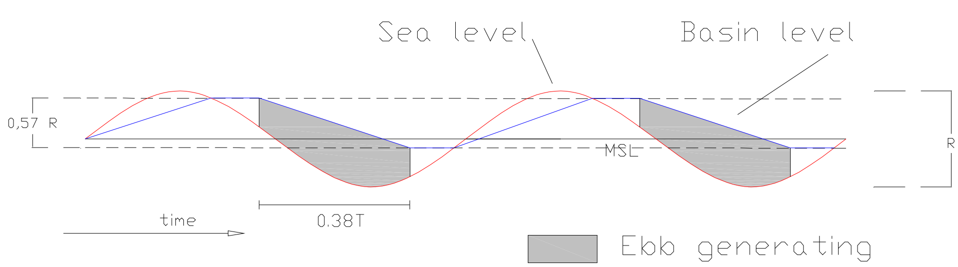


Figure A.46 One-way flood generation scheme

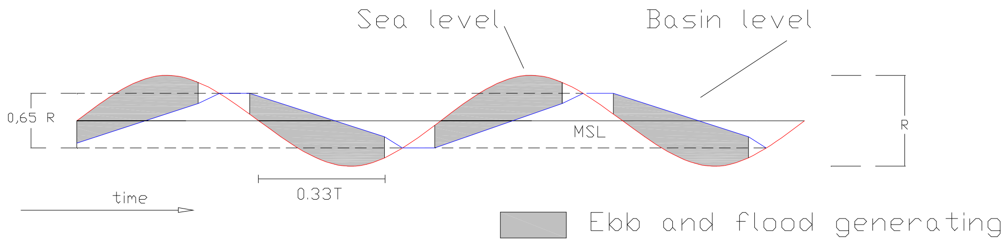


Figure A.47 Two-way generation scheme

Previous tables can be summarized in the following table:

Table A.8 Summary properties for general generation modes from DTP Model Schemes

	One-way ebb generation	One-way flood generation	Two-way generation
h_{req}	0.28R	"	"
h_{mean}	0.46R	"	0.39R
h_{max}	0.56R	"	0.46R
R_{bas}	0.57R	"	0.65R
$T_{generation}$	0.38T	"	0.33T
$T_{t,generation}$	0.38T	"	0.66T
$H_{bas,high}$	0.44R	0.13R	0.37R
$H_{bas,low}$	-0.13R	-0.44R	-0.28R
$H_{bas,mean}$	0.15R	-0.15R	0.04R

A6 Resulting power output

Distinction will have to be made in mean power output during generation and mean power output per tidal period, which takes into account periods without generation.

Mean power output during generation

The mean power output in the site selection phase can be determined by:

$$P_{t,mean} = \rho \cdot A_{t,turbine} \cdot \sqrt{2} \cdot g^{3/2} \cdot h_{netto,mean}{}^{3/2} \cdot \eta_{turbine} \cdot \eta_g \text{ (MW)} \tag{A-1}$$

Most of the parameters in the equation above remain constant; except $A_{t,turbine}$, h_{mean} and $\eta_{turbine}$ (see Table 2.1 and 4.2). This results in:

$$\text{With } \beta = \alpha_{A,scheme} \cdot h_{netto,mean}{}^{3/2} \cdot \eta_{turbine} \tag{A-2}$$

$$P_{t,mean} = \frac{\beta \cdot \rho \cdot A_{bas,0} \cdot \sqrt{R} \cdot g \cdot \eta_g}{T} \text{ (MW)} \tag{A-3}$$

As mentioned before, research has resulted in certain values for dimensionless factor $\alpha_{A,scheme}$ (see subsection 4.2.3, Table 4.3). For the mean power output, only the values for the cost efficient optimum will be used to determine the mean power output for the plant.

Mean power output per tidal period

From the mean power output during generation the mean power output per tidal period can be deduced:

$$P_{t,mean/T} = \frac{P_{t,mean} \cdot T_{t,generation}}{T} \text{ (MWs/s = MW)} \tag{A-4}$$

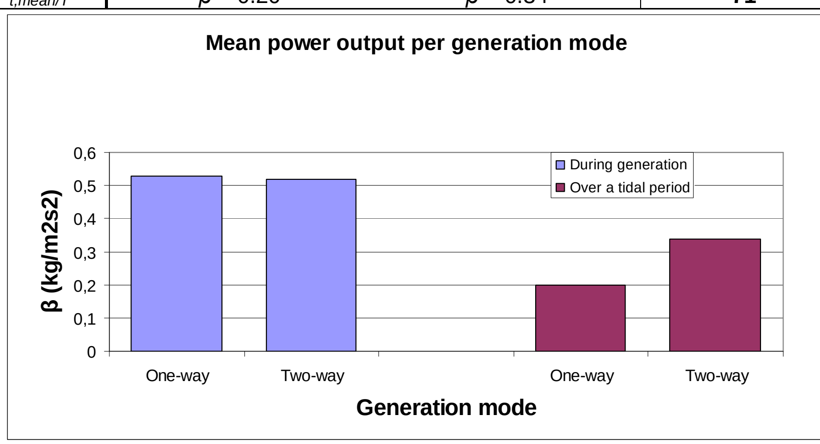
The energy production is related to the mean power output per tidal period.

Results

With the help of the preceding equations and Table A.8, the following table was made:

Table A.9 Total mean power output for cost efficient plant design

	One-way generation	Two-way generation	**Difference (%)**
$P_{t,mean}$	β = 0.53	β = 0.52	**2**
$P_{t,mean/T}$	β = 0.20	β = 0.34	**71**



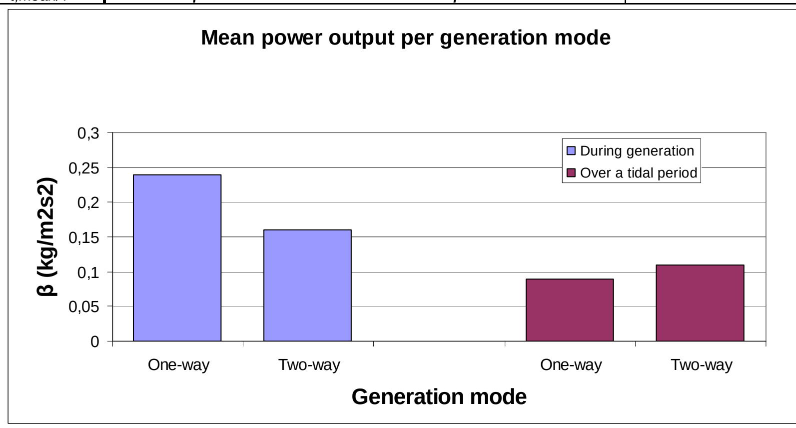
The figure above clearly shows that the power output during generation for One-way generation is about the same for Two-way generation. This is merely caused by the fact that the larger mean head difference for the One-way generation is compensated by the larger $\alpha_{A,scheme}$ for the Two-way generation. Most essential aspects is the fact that a higher power output during generation does not imply a higher power output level over a tidal period. This is a result of the longer overall generation periods for Two-way generation, which exceeds in influence of the head difference.

As for tidal power plants only the mean power over a tidal period counts, Two-way generation produced 71% more energy than One-way generation at the cost efficient design point.

But what will be the result when no difference will be made in the number of turbines between One-way and Two-way generation. Taking a constant $\alpha_{A,scheme}$ of 1 makes it less profitable however a more valid comparison, see table below.

Table A.10 Total mean power output for an equal number of turbines

	One-way generation	Two-way generation	**Difference (%)**
$P_{t,mean}$	β = 0.24	β = 0.16	**-50**
$P_{t,mean/T}$	β = 0.09	β = 0.11	**19**



This illustration proofs the fact that Two-way generation generates more energy than One-way generation (19% more) for an equal number of turbines!

B Site Selection

B1 General generation schemes

The average head h_{mean} between basin level and sea level and the generation period $T_{generation}$ will have to be determined for the different generation modes. To start with, a general basic model will be set up expanding it with proper formulations for One-way and Two-way generation.

Basic model

In the first place, the basin level remains constant at MSL. The outer sea level is determined by the tide, with a tidal range R. The sea level H_{sea} can be defined by:

$$H_{sea} = \tfrac{1}{2} \cdot R \cdot \sin(\omega \cdot t) \quad \text{(m)} \tag{B-1}$$

This is illustrated in the figure below:

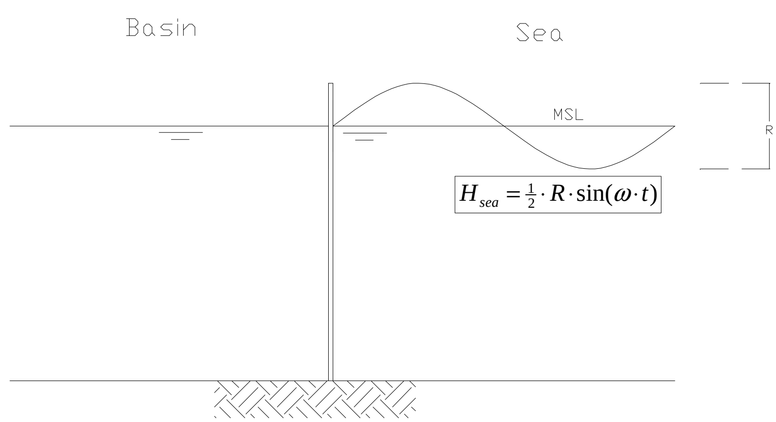


Figure B.1 First step schematisation simplified interaction sea level – basin level

To determine the mean distance s_{mean} from sea level to MSL, the average difference with the MSL for a period of ½T, the surface area under the sinusoid has to be determined divided by ½T. This can be done according to:

$$s_{mean} = \frac{1}{\tfrac{1}{2} \cdot T} \int_0^{\pi} \tfrac{1}{2} \cdot R \cdot \sin(\omega \cdot t) \quad \text{(m)} \tag{B-2}$$

This results in the following mean distance s_{mean}:

$$s_{mean} = \frac{R}{\pi} = 0.32 \cdot R \quad \text{(m)} \tag{B-3}$$

This can be illustrated by the following figure:

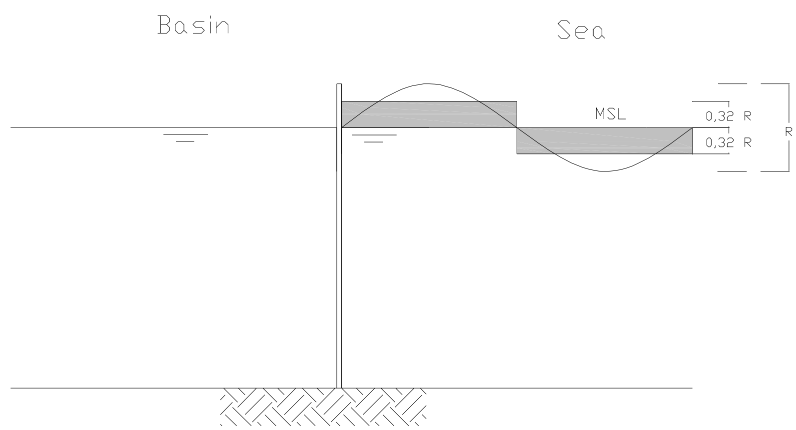


Figure B.2 Second step schematisation simplified interaction sea level – basin level

With these results the following step is; *to assume that the basin level varies with the estimated s_{mean} with the MSL as reference level.* This means that the former assumption of taking the basin level constant on MSL will be rejected from now on. Figure B.3 illustrates a basin range of 0.64*R*, twice the height of the grey bars (Figure B.2)

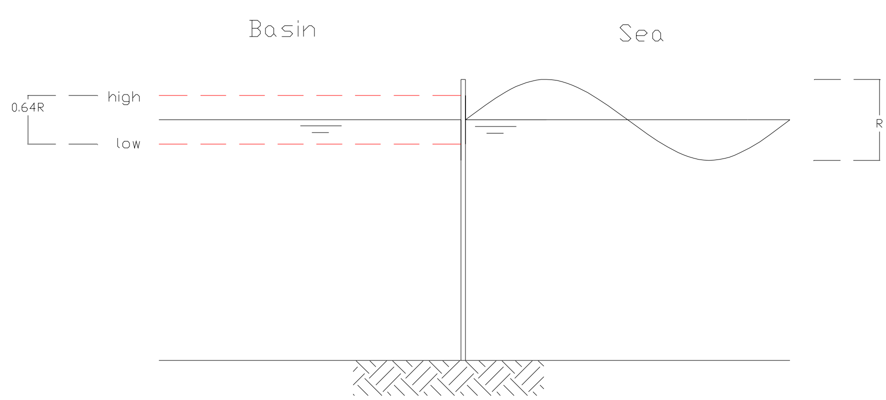


Figure B.3 Third step schematisation simplified high and low basin level

Whether this water level change of 0.64*R* remains realistic for both generation modes, will have to be analysed.

Various generation modes
To define the required parameters for the power output, the basic model can be further worked out by implementing the typical generation schemes for the three generation modes.

A schematization for a possible One-way flood generation mode is shown in Figure B.4, from where the head *h* and the generation period $T_{generation}$ can be derived. Here, MSL will be taken as reference level and thus will be equal to 0.

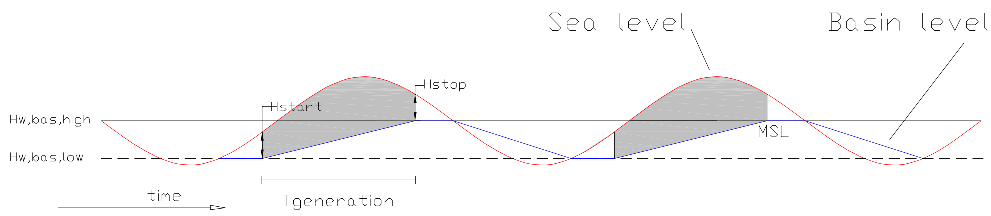


Figure B.4 Unknown parameters within generation scheme

For tidal power plants turbines require a minimum head h_{start} over the turbine to operate and a head h_{stop} ending the generation process. This is clearly shown at the start and end of the generation period $T_{generation}$ in the figure above, which is the time between h_{start} and h_{stop}. The basin range R_{bas} is the last unknown parameter which will expect to be a function of the tidal range R and will be determined by the lower and upper water levels in the basin; $H_{bas,low}$ and $H_{bas,high}$.

There is no reason to presume the h_{start} and h_{stop} to be unequal, so from now on only one required generation head h_{req} will used for further study.
This practical feasibility criterion is determined by the turbine producer. Each type of turbine requires a minimum head differences over the turbines for a sufficient pressure build up to run at a reasonable efficiency level.

By taking a constant small h_{req} of 2 m (see section 5.6), the generation period increases, but power output decreases as power is a function of $h_{req}^{3/2}$. Maximum power output can be reached by generating at maximum possible head, but then much smaller generation periods are possible, which have negative effect on the total energy output.
It will therefore be expected that h_{req} is a function of the tidal range and will not be fixed in meters as each site has other tidal characteristics.

Present plant designs and feasibility studies
From present plant design and feasibility study schemes it could be possible to derive a general generation scheme for each generation mode. Scheme characteristics were gathered from the Severn Tidal Power Groep, Wilson and Hydro Tasmania.
These schemes showed a h_{req} fluctuating around the value of 0.32R, with a minimum of 2 m as mentioned above. Herein, no difference could be found in the h_{req} between One-way and Two-way generation schemes (La Rance). This result will be implemented in the general generation schemes. As the other scheme parameters vary per generation mode, distinction will be made between One-way and Two-way generation.

<u>One-way generation scheme</u>
A realistic ending point for the generation period is when H_{bas} reaches MSL (Hydro Tasmania, 2001). As the basin range R_{bas} is smaller than the tidal range; the highest basin levels are lower than the highest sea level and lowest basin levels are higher than the lowest sea levels.
The studied schemes showed that, $H_{bas,high} \approx 0.8*H_{sea,high}$ for One–way ebb generation. This means that $H_{bas,high}$ is 0.4R, as is illustrated by the next figure.

So, the following realistic averaged starting and end points for generation will be used as input:

Start generating (sea level, basin level):	H_{sea}= 0.08R	H_{bas}= 0.4R
End generating (sea level, basin level):	H_{sea}= -0.32R	H_{bas}= 0

This results in a generation time of 0.83π per cycle for the One-way generation model.

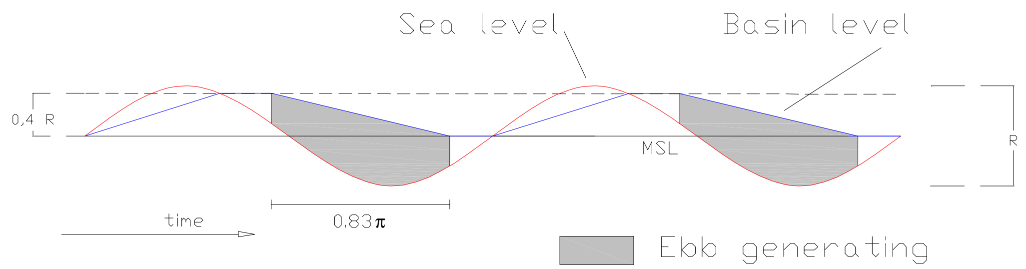


Figure B.5 Averaged One-way ebb generation scheme

For the One-way flood generation, the scheme will be opposite and look like the figure below:

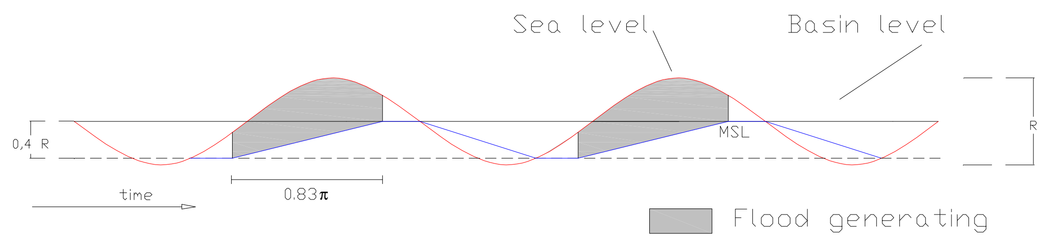


Figure B.6 Averaged One-way flood generation scheme

To define the mean head during generation, the generation surface (grey area) has to be derived first before dividing by the generation period. This will be done in the section below.

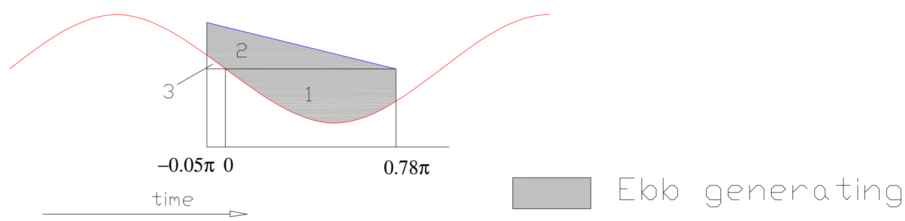


Figure B.7 Mean head calculation

$$Generation = Surface1 + Surface2 - Surface3$$

$$Surface1 = \int_0^{0.78\pi} -\tfrac{1}{2} \cdot R \cdot \sin(\omega \cdot t) = 0.89 \cdot R$$

$$Surface2 = \tfrac{1}{2} \cdot 0.83 \cdot \pi \cdot 0.4 \cdot R = 0.52 \cdot R$$

$$Surface3 = \int_{0.95\pi}^{\pi} \tfrac{1}{2} \cdot R \cdot \sin(\omega \cdot t) = 0.01 \cdot R$$

$$Generation = R \cdot (0.89 + 0.52 - 0.01) = 1.4 \cdot R \qquad \text{(B-4)}$$

From the result of B-4 and Figure B.8 the mean tidal head for One-way generation $h_{mean,one}$ can be derived:

$$h_{mean,one} = \frac{1.4 \cdot R}{0.83 \cdot \pi} = 0.54 \cdot R \qquad \text{(m)} \tag{B-5}$$

Two-way generation scheme

To model the mean head for a Two-way generation the same base is needed as for One-way generation. Differences however can be found in the moments and periods to generate and the average head over that period.

The studied schemes showed that the upper and lower basin levels to vary from about +0.32*R* to -0.32*R*, so that R_{bas} is approximately 0.64*R*.
To come to the generation scheme for Two-way generation a line was drawn from A to B, see Figure B.8. In order to arrive to the generation period the distance, from this line for H_{bas} to the line for H_{sea}, should be at least larger than 0.32*R*.
This means that the following starting and ending points are derived.

Start ebb generating	(sea level, basin level):	H_{sea}= 0	H_{bas}= 0.32*R*
End ebb generating	(sea level, basin level):	H_{sea}= -0.48*R*	H_{bas}= -0.16*R*
Start flood generating	(sea level, basin level):	H_{sea}= 0	H_{bas}= 0.32*R*
End flood generating	(sea level, basin level):	H_{sea}= 0.48*R*	H_{bas}= 0.16*R*

This results in a generation time of 0.59π per cycle for Two-way generation.

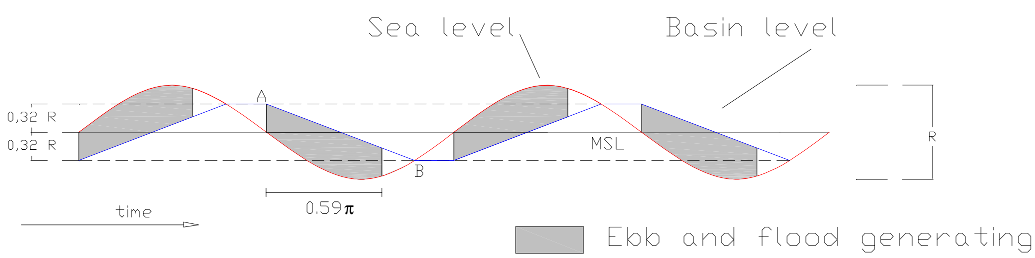


Figure B.8 Averaged Two-way generation scheme

The mean head $h_{mean,two}$ can now be defined by:

$$h_{mean,two} = \frac{1}{0.59 \cdot \pi} \cdot \int_0^{0.59\pi} 0.32 \cdot R - \frac{0.64 \cdot R}{0.78 \cdot \pi} \cdot t + \tfrac{1}{2} \cdot R \cdot \sin(\omega \cdot t) = 0.42 \cdot R \qquad \text{(m)} \tag{B-6}$$

Results
The results from the preceding schemes can be summarized in the following table:

Table B.1 Summary properties for different generation modes from averaged schemes

	One-way ebb generation	One-way flood generation	Two-way generation
h_{req}	0.32*R*	“	“
h_{mean}	0.54*R*	“	0.42*R*
h_{max}	0.68*R*	“	0.48*R*
R_{bas}	0.40*R*	“	0.64*R*
$T_{generation}$	0.42*T*	“	0.30*T*
$T_{t,generation}$	0.42*T*	“	0.59*T*
$H_{bas,high}$	0.40*R*	MSL	0.32*R*
$H_{bas,low}$	MSL	-0.40*R*	-0.32*R*
$H_{bas,mean}$	0.20*R*	-0.20*R*	MSL

These scheme characteristics can be compared with the scheme characteristics from the DTP Model (Appendix A5).

B2 Derivation basin shape parameter λ

The derivation for the shape and scheme parameter λ will be worked out.

$$\lambda = \left(\frac{R + H_{bas,mean,scheme}}{R}\right)^{\sqrt{\frac{4 \cdot A_{bas,MHW}}{3 \cdot A_{bas,0}} - \frac{4}{3}}} \quad (-) \qquad \text{(B-7)}$$

The first part of the equation between the brackets deals with the various scheme options, where the mean basin depth $H_{bas,mean,scheme}$ varies per scheme.

The second part represents the possible shape variations of the basin. In case of a rectangular basin the basin surface area remains the same for each water level elevation, this mean for $\lambda=1$, the part under the square root must be equal to zero.
The equation should also be able to represent the more complex scenario, the upper bound tidal basin shape, which can be found in de figure below.

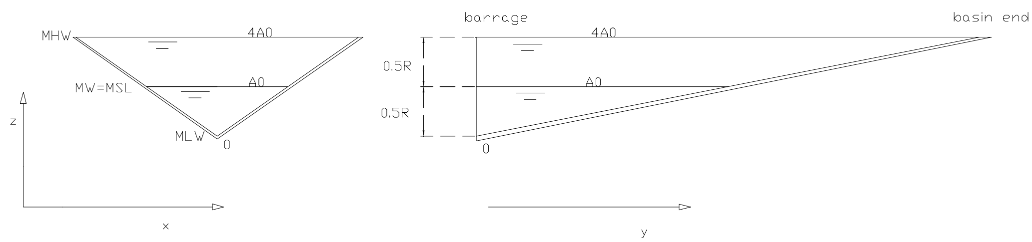


Figure B.9 Upper bound basin shape scenario

This means that equation must show that for the basin surface area at MHW, which is twice the water level at MSL, is 4 times the surface area at MSL. A doubling of the water level results in the multiplication by four of the surface area, which shows a quadratic relation for this scenario. The square root in the equation solves this problem, completing the equation.

The lower bound and upper bound basin shapes are discussed, the possibilities in between was assumed to follow equation B-7.

B3 Total turbine surface area equation

The total averaged discharge $Q_{t,mean}$ through the turbines can be calculated by dividing the tidal prism by the generation period of the turbines $T_{generation}$:

$$Q_{t,mean} = \frac{h_{mean} \cdot A_{bas,0}}{T_{generation}} \quad (\mathrm{m^3/s})$$

Another way to come to a discharge is by multiplying the total turbine surface area $A_{t,turbine}$ by the flow velocity u through the turbines. This could be worked out, see equations below:

$$Q_{t,mean} = A_{t,turbine} \cdot u_{mean} \quad (\mathrm{m^3/s})$$

$$u_{mean} = \sqrt{2 \cdot g \cdot h_{mean}} \quad (\mathrm{m/s})$$

$$Q_{t,mean} = A_{t,turbine} \cdot \sqrt{2 \cdot g \cdot h_{mean}} \quad (\mathrm{m^3/s})$$

$$\frac{h_{mean} \cdot A_{bas,0}}{T_{generation}} = A_{t,turbine} \cdot \sqrt{2 \cdot g \cdot h_{mean}} \quad (\mathrm{m^3/s})$$

$$A_{t,turbine} = \frac{A_{bas,0}}{T_{generation} \cdot \sqrt{2 \cdot g}} \cdot \sqrt{h_{mean}} \quad (\mathrm{m^2})$$

This equation, however, will not result in an optimum turbine surface area. Therefore the formula will be rewritten and the new introduced dimensionless surface area parameter α_A will be defined by the DTP Model:

$$A_{t,turbine} = \alpha_A \cdot \frac{A_{bas,0}}{T \cdot \sqrt{2 \cdot g}} \cdot \sqrt{R} \quad (\mathrm{m^2}) \qquad \text{(B-8)}$$

B4 Total sluice gate surface area

Available data from operational tidal power plant and feasibility studies, as illustrated in Table B.2, show a clear relation between the total sluice gate surface and total turbine surface area for 5 tidal power stations.

Table B.2 Empirical approach illustrating the relation between $A_{t,turbine}$ and $A_{t,s}$

	La Rance	Mersey	Severn outer	Severn Inner	Severn 2nd stage	
$D_{turbine}$ (m)	5.35	8	9	9	9	
$N_{turbine}$ (-)	24	28	300	160	125	
$A_{t.turbine}$ (m^2)	540	1407	19085	10179	7952	
A_s per gate (m^2)	150	144	144	144	144	
N_s (-)	6	20	320	150	100	
$A_{t,s}$ (m^2)	900	2880	46080	21600	14400	**Average**
Ratio $A_{t,s}$ / $A_{t,turbine}$ (-)	1.7	2.0	2.4	2.1	1.8	**2.0**

The table shows that there is a close relation between $A_{t,turbine}$ and $A_{t,s}$; the ratio $A_{t,s}$ / $A_{t,turbine}$ appears to be varying around the average value of 2.
From this, it will be acceptable to assume the following relation:

$$A_{t,s} = 2 \cdot A_{t,turbine} \quad (\mathrm{m}^2) \qquad \text{(B-9)}$$

B5 Derivation flow velocity at barrage during closure

To estimate the occurring flow velocities during closure, first the discharge will have to be derived. The discharge then again is dependent on the water level movement inside the basin.

To start with, the water level variation can be calculated according to:

$$H_{bas} = \tfrac{1}{2} \cdot R_{bas} \cdot \sin(\omega \cdot t - \theta) = r \cdot \tfrac{1}{2} \cdot R_{sea} \cdot \sin(\omega \cdot t - \theta) \qquad \text{(m)} \qquad \text{(B-10)}$$

Here, the angular velocity ω for tides is:	$1.4 \cdot 10^{-4}$ rad/s	for a semi-diurnal tide
	$7.0 \cdot 10^{-5}$ rad/s	for a diurnal tide

Now, the amplitude ratio r and the phase difference θ with the sea level outside have to be calculated. For the amplitude ratio first the dimensionless parameter Γ have to be introduced.

$$\Gamma = \frac{8}{3 \cdot \pi} \cdot \left(\frac{A_0}{A_{closure}} \right)^2 \cdot \frac{\omega^2 \cdot \tfrac{1}{2} \cdot R_{sea}}{g} \qquad (-) \qquad \text{(B-11)}$$

Where;

For $0.1 < \Gamma < 10$ $\quad r = \dfrac{1}{\Gamma \cdot \sqrt{2}} \cdot \sqrt{-1 + \sqrt{1 + 4 \cdot \Gamma^2}}$

For $\Gamma < 0.1$ $\quad r \cong -1 + 2 \cdot \Gamma^2$

For $\Gamma > 10$ $\quad r \cong \dfrac{1}{\sqrt{\Gamma}}$

The phase difference can be calculated according to:

$$\theta = \arccos r \qquad \text{(rad)} \qquad \text{(B-12)}$$

To find the flow velocity, the discharge distribution in time is not of any importance, but the discharge amplitude $\hat{Q}$ is, written as:

$$\hat{Q} = A_{bas} \cdot \omega \cdot \hat{H}_{bas} = A_{bas} \cdot \omega \cdot r \cdot \hat{H}_{sea} = \tfrac{1}{2} \cdot A_{bas} \cdot \omega \cdot r \cdot R \qquad (\text{m}^3/\text{s}) \qquad \text{(B-13)}$$

This discharge amplitude represents the highest possible discharge and thus the highest flow velocity, which is the parameter which has to be calculated.

With the help of this equation the flow velocity can be calculated by:

$$\hat{u} = \frac{\hat{Q}}{A_{closure}} \qquad \text{(m/s)} \qquad \text{(B-14)}$$

This results in the following relation between the flow velocity and the other site specific parameters:

$$\hat{u} \propto A_{bas}, \omega, r, R, \frac{1}{A_{closure}} \qquad \text{(m/s)} \qquad \text{(B-15)}$$

Before the expected flow velocities can be determined, first the following information is required:

- The largest barrage opening surface area A_{open} during operation
- The minimum required (time)window $t_{closure}$ for closure

If sluice gates and turbines are all open, maximum barrage opening surface area can be reached. As determined in B4, this is about 3 times the total turbine surface area. Only the cost efficient plant design will be considered.
With the help of Table 7.4 this results in the following opening surface for One-way generation:

$$A_{t,open,one} = \frac{6.6 \cdot A_0 \cdot \sqrt{R}}{T \cdot \sqrt{2 \cdot g}} \qquad (m^2) \tag{B-16}$$

And for Two-way generation:

$$A_{t,open,two} = \frac{9.6 \cdot A_0 \cdot \sqrt{R}}{T \cdot \sqrt{2 \cdot g}} \qquad (m^2) \tag{B-17}$$

Before construction of the barrage, A_{open} will be equal to $A_{closure}$. When the barrage construction is completed, A_{open} will follow formula B-16 or B-17 depending on the mode of operation.

For the Severn barrage a 60 minute window was calculated sufficient to close of the last part of the barrage with turbine caissons (Institution of Civil Engineers, 1982). Therefore, the same time window $t_{closure}$ will be suggested.

The preceding can be illustrated by the following example, clearly showing the effect of the closure to water level, phase difference and flow velocity.

Illustration
The preceding method will be illustrated by an example with the following input:

Table B.3 Parameter values for illustration

R (m)	A_0 (m^2)	$A_{closure}$ (m^2)	ω (rad/s)	Generation mode
8	$10*10^6$	8000	$1.4*10^{-4}$	One-way

In Figure B.10 the water level variations are plotted for different phases during the closure procedure, from before construction (100% open) to after construction (7% open) according to B-16. The situation where the opening ratio is 1 will thus be equal to the sea level elevation.
The chart clearly shows a smaller basin amplitude from 4 m about 3.5 m in combination with a phase difference.

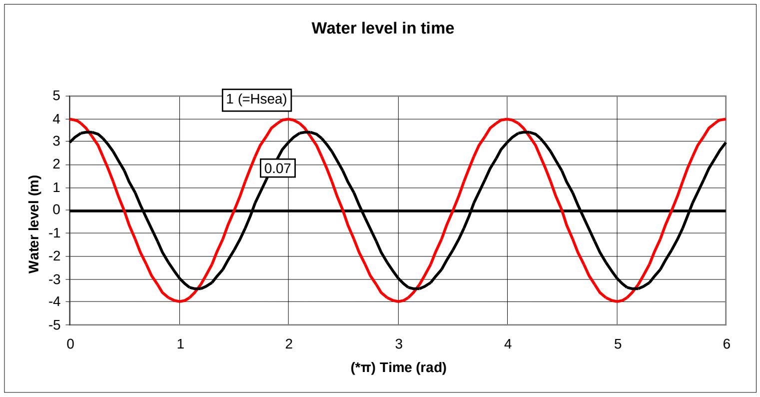


Figure B.10 Basin level for varying opening area

Described by the different equations before, the flow velocities vary with the sea level elevation, which can be expressed by tidal range *R* (Figure B.11) and with the barrage opening ratio (Figure B.12). Both are plotted in the graphs below.

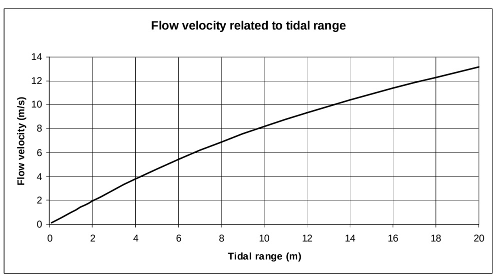


Figure B.11 Flow velocity as function of tidal range for a 0.07 opening ratio

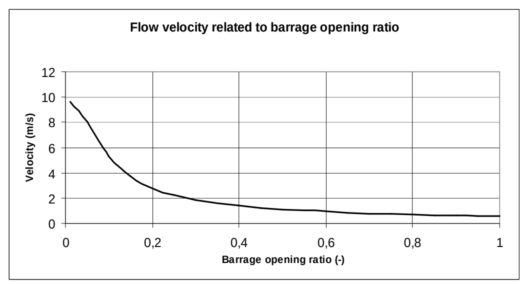


Figure B.12 Flow velocity as function of the opening ratio for R=8m

These graphs can be combined into one figure:

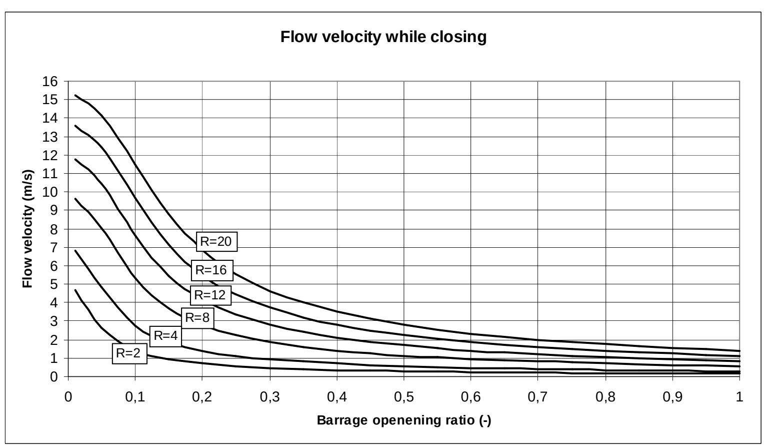


Figure B.139 Flow velocity for various opening areas and tidal ranges

This illustration has given a clear view on the flow velocity development by varying some parameters.

B6 Interim feasibility number κ_1 for operational plants and feasibility studies

Table B.4 Site specific parameter values for La Rance tidal power plant (operational) and the Severn and the Mersey tidal power plant (feasibility studies).

	s_{grid} (m)	P_{pot} (MW)	$H_{w,barrage,mean}$ (m)	R (m)	$L_{barrage}$ (m)	$A_{bas,0}$ (m^2)
La Rance	$50*10^3$	154	10	7.9	750	$22*10^6$
Severn	$30*10^3$	2642	20	7	15900	$479*10^6$
Mersey	$20*10^3$	277	9	7.4	1700	$60*10^6$

Table B.5 The site potential defined by interim feasibility number κ_1.

	r_{grid}	r_d	r_l	$\boldsymbol{\kappa_1}$
La Rance	0.17	0.18	0.04	**0.38**
Severn	0.01	0.91	0.20	**1.12**
Mersey	0.04	0.22	0.06	**0.32**

C Economical analysis

C1 Construction costs

Powerhouse

The powerhouse costs C_p can be calculated by multiplying the powerhouse volume V_p by the unit cost for powerhouse material B_p[b], which is about 416 $/m^3 for different case studies (Fay and Smachlo, 1983 I).

$$V_{p,bulb} = N_{turbine} \cdot 20.2 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.3 \cdot D_{turbine}) \ (\mathrm{m}^3) \quad \textit{(3-11)}$$

$$V_{p,straflo} = N_{turbine} \cdot 14.5 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.2 \cdot D_{turbine}) \ (\mathrm{m}^3) \quad \textit{(3-12)}$$

With this, the following powerhouse costs C_p can be determined:

$$C_{p,bulb} = 416 \cdot N_{turbine} \cdot 20.2 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.3 \cdot D_{turbine}) \ (\$) \quad \text{(C-3)}$$

$$C_{p,straflo} = 416 \cdot N_{turbine} \cdot 14.5 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.2 \cdot D_{turbine}) \ (\$) \quad \text{(C-4)}$$

Sluice gates

Multiplying volume V_s (formula 3-15) by the unit costs for a sluice gate unit B_s[c] of 457 $/m^3 (Fay and Smachlo, 1983 I) results in the construction costs for the sluice gates C_s, see formula C-5.

$$V_s = N_{turbine} \cdot 11.5 \cdot D_{turbine}{}^2 \cdot H_c \quad (\mathrm{m}^3) \quad \textit{(3-15)}$$

The unit costs for the sluice gates are higher than the unit costs for the powerhouse, as the sluice gates do not only take into account the concrete caisson but also include the gates and mechanical equipment:

$$C_s = B_S \cdot N_{turbine} \cdot 11.5 \cdot D_{turbine}{}^2 \cdot H_c = 5278 \cdot N_{turbine} \cdot D_{turbine}{}^2 \cdot H_c \ (\$) \quad \text{(C-5)}$$

---

[b] For 2006, is the result of taking into account a 2% inflation over 23 years from 264 $/m^3

[c] For 2006, is the result of taking into account a 2% inflation over 23 years over 290 $/m^3

Barrage dam

Multiplying the volume V_{dam} by the unit costs for a barrage B_{dam}[d], about 19 \$/m^3 (Fay and Smachlo I), results in the total capital costs for the barrage C_{dam}.

$$V_{dam} = L_{dam} \cdot A_{dam} = L_{dam} \cdot (10 \cdot H_c + m \cdot H_c^{\ 2}) \quad (\mathrm{m}^3) \qquad (3\text{-}17)$$

$$\boxed{C_{dam} = 19 \cdot (L_{barrage} - 4.4 \cdot D_{turbine} \cdot N_{turbine}) \cdot (10 \cdot H_c + 1.75 \cdot H_c^{\ 2}) \quad (\$) \qquad (\text{C-6})}$$

Where;
$L_{barrage}$ = total barrage length, in meters (m)

Bed protection

$$V_{bed} = (2 \cdot D_{part,req}) \cdot (100) \cdot (L_p + L_s) \quad (\mathrm{m}^3) \qquad \textit{(3-25)}$$

The unit costs for bottom protection material B_{bottom} will be assumed the same as the unit costs for barrage dam material. Both consist of granular material and show therefore a strong similarity, both in material and in costs.
The barrage dam unit costs are 19 \$/m^3 (Fay and Smachlo, 1983 I). As a result the total costs for the bottom protection can be calculated according to:

$$\boxed{C_{bottom} = 19 \cdot (100) \cdot (8.8 \cdot D_{turbine}) \cdot (L_p + L_s) = 3800 \cdot D_{part,req} \cdot (L_p + L_s) \quad (\$) \qquad (\text{C-7})}$$

Transmission lines

$$B_{trans} = \frac{f185,- \cdot (1.02^{14\,years})}{2.20} = 110 \ (€/\mathrm{m}) \ \rightarrow 110 \cdot 1.264 \approx 140 \ (\$/\mathrm{m}) \qquad (\text{C-8})$$

Where;
f 185,- = the costs per meter transmission line in 1992, in Dutch guilders (DACE)
1.02 = the average inflation in the Netherlands from 1992 to 2006 (-)
2.20 = the conversion rate from € 1 to guiders, in Dutch guilders per euro
1.264 = the conversion rate from € 1 to USD, in USD per euro (X-rates)

As a result the costs for the transmission lines can be estimated using:

$$\boxed{C_{trans} = B_{trans} \cdot s_{grid} = 140 \cdot s_{grid} \quad (\$) \qquad (\text{C-9})}$$

[d] Is the result of taking into account a 2% inflation over 23 years over 12.3 \$/m^3

Turbine and electrical equipment

The electrical equipment for the project, containing the turbine and the generator, forms a large part of the project construction costs. Detailed specification are therefore essential. These specifications however, are difficult to estimate. For some operational projects the costs for electrical equipment are present, but the available data is too little and fluctuates too much to be able to draw some valid conclusions from. Therefore, the turbine producer Alstom Power France has been contacted.

Turbine costs

As mentioned earlier, the Bulb and the Straflo turbines are to be applied for tidal power. The double regulated Bulb turbine will be more expensive than the single regulated Straflo turbine as more regulation is possible. More regulation is more expensive, but increases the (average) turbine efficiency (see subsection 4.2.2).

With the input of Alstom Power France, costs estimations could be made for the Bulb turbine and will be discussed below. No other information was available for the Straflo turbine costs, so these costs are assumed to be equal to a single regulated Bulb turbine with variable guide vanes. **These costs for a single regulated Bulb turbine are about 90% of the turbine costs for a double regulated Bulb turbine (Alstom Power France)**

The graph shows different estimated turbine costs curves as function of the turbine diameter and the (design) head difference. The upper three lines describe the 7.5 m diameter and the lowest three lines the 4.5 m diameter.

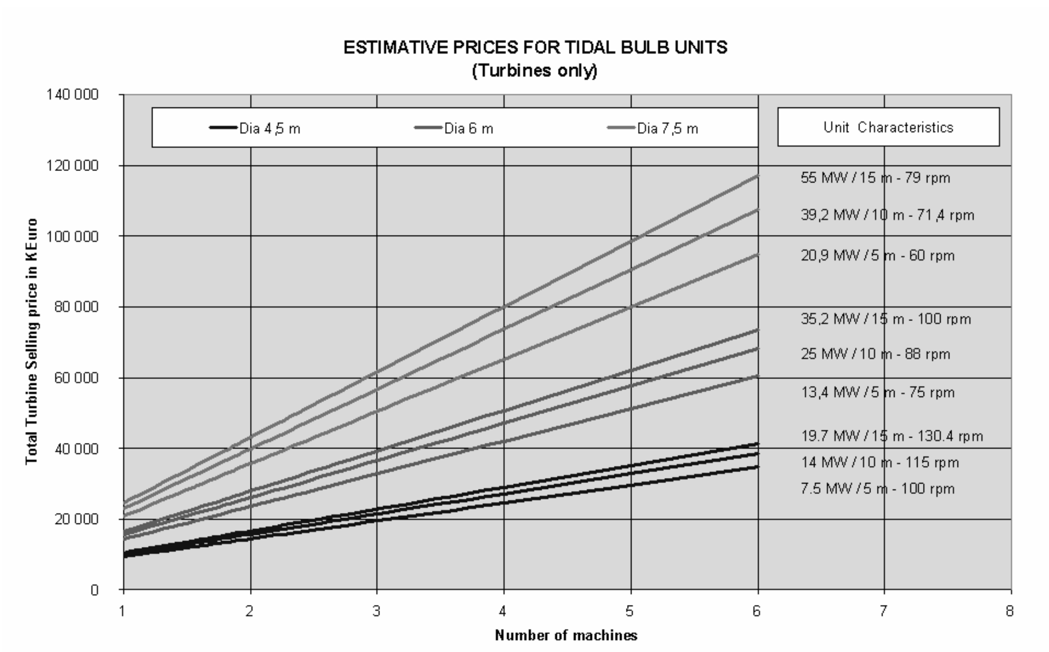


Figure C.1 Double regulated Bulb Turbine cost estimation (Alstom Power)

Where;

Dia	= turbine diameter $D_{turbine}$ (m)
15m/10m/5m	= rated head difference h_{rated} (m)

The figure shows that there are fixed starting costs for one turbine and that the costs increase linear with the number of turbines. It is expected that for a large number (say 50 turbines) each additional turbine will cost less. For such a scenario, Alstom Power anticipates a 5% discount of the total turbine costs. Increasing the turbine diameter results in higher costs, same with an increase in head difference. The influence of the diameter however is much larger than by varying the head difference.

Out of these curves it was possible to define one general function for each of these function as they cross the same point when $N_{turbine} = 0$.

The function is expected to contain the following characteristics:

- Fixed starting costs
- Some relation with the (rated) head difference h_{rated}

- Linear relation with number of turbines $N_{turbine}$
- Exponential relation with the turbine diameter $D_{turbine}$

Investigation showed that the following function fits well to the various curves:

$$C_{turbine,bulb,double} \approx 5 \cdot 10^6 + 164 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2 \quad (€) \qquad \text{(C-10)}$$

As example three scenarios are illustrated in the table below, which shows a small difference between the estimated costs from curves and derived by the function.

Table C.1 Comparison turbine costs by curves and general function

$N_{turbine}$ (-)	$D_{turbine}$ (m)	h_{rated} (m)	Turbine costs graph (€)	Turbine costs function (€)	Difference
6	4.5	5	35*10^6	35*10^6	≈ 0%
6	6	10	68*10^6	68*10^6	≈ 0%
6	7.5	15	117*10^6	114*10^6	≈ 3%

The general formula C-10 is a very useful and an easy method to make a first estimation for turbine cost estimation. It also contains the characteristics and parameter relations which were expected beforehand.

Finally, formula C-10 will be transposed from Euro to USD (1 Euro = 1.264 USD (X-Rates Oct 2006)) and the following equation can be presented:

$$C_{turbine,bulb,double} \approx 6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2 \quad (\$) \qquad \text{(C-11)}$$

$$C_{turbine,straflo} = C_{turbine,bulb,single} \approx 0.9 \cdot (6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2) \ (\$) \qquad \text{(C-12)}$$

Further electrical equipment costs
Turbines require electrical equipment to convert movement into electricity with the generator as main unit. **The whole package of electrical equipment, containing generator, controls etc, will form about 50% of the turbine costs** (Alstom Power France).

With this estimation the most suitable generator capacity is applied, varying the turbine diameter and head difference.

Total costs
As a result, the following costs can be considered containing the turbine costs and the electrical equipment:

$$C_{turbine+g,bulb,double} \approx 1.5 \cdot (6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2) \quad (\$) \qquad \text{(C-13)}$$

$$C_{turbine+g,straflo} = C_{turbine+g,bulb,single} \approx 1.35 \cdot (6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2) \ (\$) \qquad \text{(C-14)}$$

Total construction costs

Since all capital costs are worked out separately, the total project construction costs can be determined by:

$$C_t = C_p + C_{turbine+g} + C_s + C_{dam} + C_{bottom} + C_{trans} \qquad (\$) \qquad \text{(C-15)}$$

C2 Cost reference level

Electricity generation sources

The following types of electricity sources will be taken into account; coal, gas, nuclear, biomass, hydropower and onshore wind power.

An electricity generation selection should include:

- Large variety in electricity sources
- Main conventional and emerging generation types

For the selected sources, conventional and emerging generation can be classified as follows:
Conventional generation: Coal, gas, hydropower and nuclear power.
Emerging generation: Biomass and wind power

Besides the absence of oil as a generation source, due to a lack of data, the presented selection meets the determined criteria and can therefore been seen as valuable representation.

Overnight construction costs

In the text all dollars ($) and dollar cents ($c) stand for USDollar(cents).

The overnight construction costs are the relative capital costs[e] of a project if it would be constructed overnight, in $/kW. Therefore, a power plant with higher power capacity, but same capital costs, will result in lower overnight construction costs.
Each of the above mentioned electricity sources has its own typical overnight construction costs.
The construction of a tidal power plant might for example start in 10 or 20 years from now. Converting all finances to these years will bring along some extra inaccuracies caused by several predictions on energy prices and currency factors.
Therefore, for simplicity reasons, all finances are converted to present 2006 level.

The table below (Table C.2) shows the obtained overnight construction cost predicted data from 2005 and 2010 in $/kW for the various electricity sources and are representative for the United States.

Table C.2 Overnight construction costs by electricity source for 2005, 2010 and 2006 (Tayler, 2001)

	Overnight construction costs (*$/kW*)		Derived (*$/kW*)
	2005	**2010**	**2006**
Gas	429	381	419
Wind	763	763	763
Coal	1029	953	1014
Biomass	1449	1335	1426
Nuclear	1525	1411	1503
Hydro	1716	1620	1697

2006 data was obtained by derivation from the 2005 and 2010 prediction, using the following formula:
2006$/kW = 2005$/kW - $^{2}/_{5}$*(2005$/kW - 2010$/kW)

The 2006 values are plotted in Figure C.2.

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[e] Capital cost is the total investment needed to complete a project and bring it to a commercial operable status, the cost of construction of a new plant.

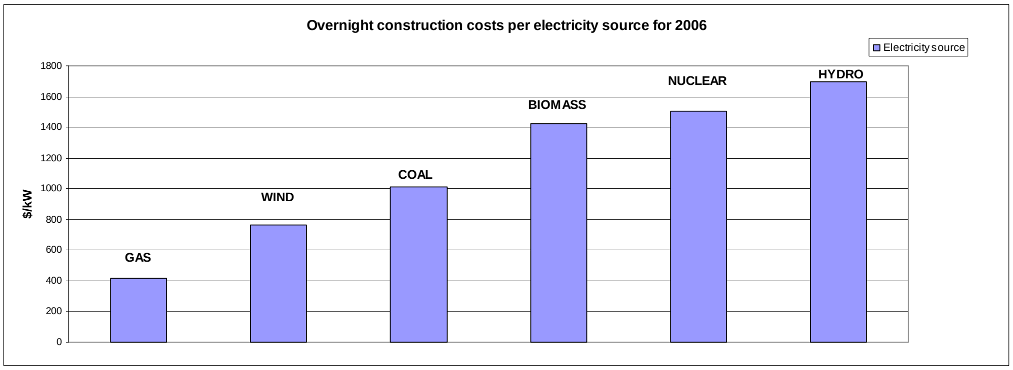


Figure C.2 Overnight construction costs per electricity source (2006) (Tayler, 2001)

The numbers which are to be mentioned in this chapter, such as different costs per electricity source, are representative for the United States. *Because no reliable global information was found, these numbers for the United States are assumed to represent global numbers (costs).*
The author is aware that these numbers form a base for the final conclusion of the thesis and will therefore mention this assumption and its final consequences.
Figure C.2 clearly shows the positive position of wind power as the first renewable sources in the list, while the construction of conventional hydroelectric plants has high capital costs. This is probably the result of a shortage of space for new hydroelectric projects in the United States. The low overnight construction costs for wind on the other hand could only be generated by government subsidies.

Levelized electricity costs

Beside the overnight construction costs it would be valuable to take the pure electricity generating costs as a second reference level. However, pure generating data for various electricity sources appeared to be incomplete[f] and inconsistent[g] and therefore the levelized electricity costs will be used as reference level. The consequence is that the capital cost now have influence on both the overnight construction costs and the levelized electricity costs.

However, the levelized electricity costs partly represent the generating costs after the initial investment and are therefore of great importance. A generation method for example, which appears interesting because of its low investment costs, could loose the competition with others when it implies higher costs for generation.

The table below (Table C.3) shows the obtained levelized cost predicted data from 2005 and 2010 in $c/kWh for the various electricity sources and are representative for the United States.

[f] Literature sometimes showed a lack of information where no 2006 prediction could be made or did not represent the main generation methods.
[g] Literature sometimes showed inconsistent use of value definitions so that values could not be compared with each other.

Table C.3 Levelized electricity costs by electricity source for 2005, 2010 and 2006 (Tayler, 2001)

	Levelized electricity costs *$c/kWh*		Derivative *$c/kWh*
	2005	**2010**	**2006**
Wind	2.9	2.6	2.9
Gas	3.1	3.0	3.1
Coal	3.3	3.1	3.3
Nuclear	4.5	4.3	4.5
Hydro	5.5	5.2	5.5
Biomass	5.7	5.2	5.6

2006 data was obtained by derivation from the 2005 and 2010 prediction, using the following formula:
2006$c/kWh = 2005$c/kWh - $^2/_5$*(2005$c/kWh - 2010$c/kWh)

The levelized electricity costs which are to be found in Figure C.3.

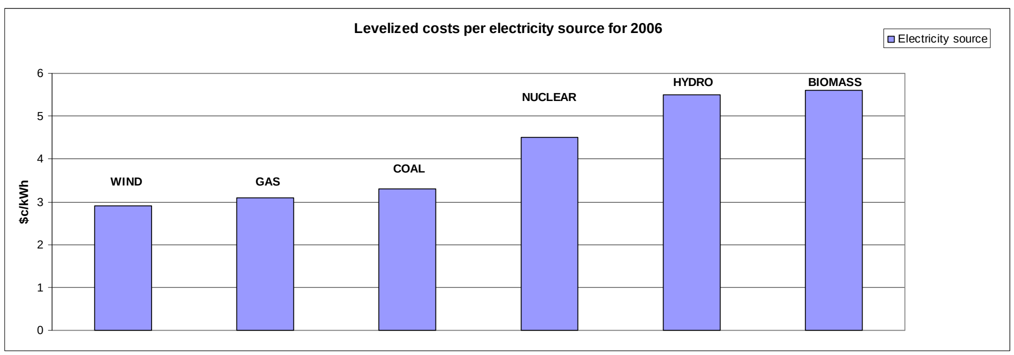


Figure C.3 Levelized costs per electricity source (2006) (Tayler, 2001)

The explanation of the high levelized electricity costs for hydroelectric power and low costs for wind energy are expected to be the same as described for the overnight construction costs.

Capacity factor

Each generating resource has its own capacity factor, also called plant factor, which could have a great influence on the amount of produced energy compared to the rated production. Take notice that this plant factor is already included in the levelized electricity costs for comparative electricity sources.
As illustration, capacity factors for the main electricity sources in the UK during 2004 is illustrated by Figure C.4, which clearly shows the high capacity factor for the conventional generating sources compared to wind as emerging generating source (Sinden, 2005).

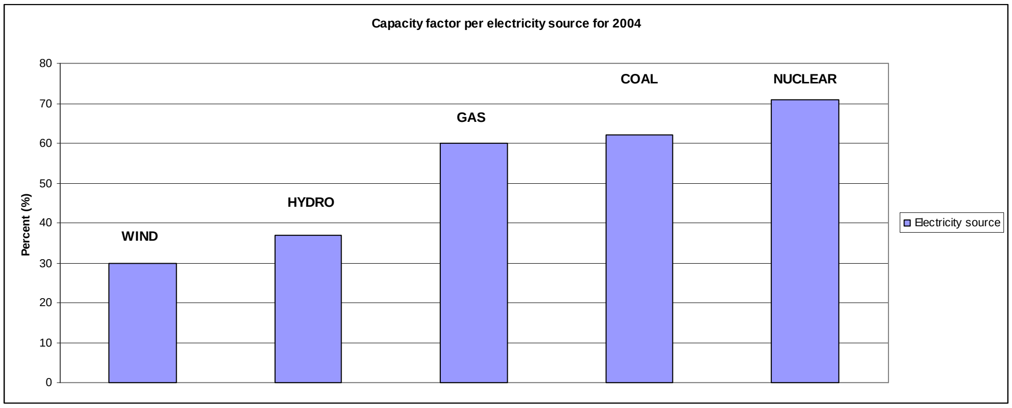


Figure C.4 Capacity factor per electricity sources (2004) (Sinden, 2005)

C3 Costs tidal energy

Ideal total construction costs C_t

The highest feasibility for tidal power will be created for a site where:

- No dam is required $C_{dam} = 0$
- No bed protection is required $C_{bed} = 0$
- Site is located on electricity grid $C_{trans} = 0$

Further:

- $H_{wave,sign} = 0$
- The site has a large tidal range R=10 m
- The site has a large basin surface area $A_{bas,0}$ = 10 km^2
- The site has a semi-diurnal tide T= 44712 s
- $R_{MHWS\text{-}MLWS} \approx 1.5*R$ =15 m
- Two-way generation will take place, using double regulated Bulb turbine
- MSL = 10
- $D_{turbine}$ = 5 m
- $H_{sea,0}$ =10 m

$$C_t = C_p + C_{turbine+g} + C_s \quad (\$)$$

$$C_{p,bulb} = 416 \cdot N_{turbine} \cdot 20.2 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.3 \cdot D_{turbine}) \quad (\$)$$

$$C_{turbine+g,bulb,double} \approx 1.5 \cdot (6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2) \quad (\$)$$

$$C_s = B_S \cdot N_{turbine} \cdot 11.5 \cdot D_{turbine}{}^2 \cdot H_c = 5278 \cdot N_{turbine} \cdot D_{turbine}{}^2 \cdot H_c \quad (\$)$$

$$C_t = 9.45 \cdot 10^6 + N_{turbine} \cdot D_{turbine}{}^2 \cdot (8403 \cdot (R_{MHWS-MLWS} + 2.3 \cdot D_{turbine}) + 0.31 \cdot 10^6 \cdot \sqrt[4]{h_{rated}} + 5278 \cdot (H_{sea,0} + 0.5 \cdot R_{MHWS-MLWS})) \,(\$)$$

$$C_t = 9.45 \cdot 10^6 + N_{turbine} \cdot D_{turbine}{}^2 \cdot (8403 \cdot (1.5 \cdot R + 2.3 \cdot D_{turbine}) + 0.25 \cdot 10^6 \cdot \sqrt[4]{R} + 5278 \cdot (10 + 1.5 \cdot R)) \quad (\$)$$

With;

$$N_{turbine} = \frac{0.92 \cdot A_{bas,0} \cdot \sqrt{R}}{T \cdot D_{turbine}{}^2} = 26 \text{ (-)}$$

the following can be written:

$$C_t = 9.45 \cdot 10^6 + 26 \cdot 5^2 \cdot (8403 \cdot (1.5 \cdot 10 + 2.3 \cdot 5) + 0.25 \cdot 10^6 \cdot \sqrt[4]{10} + 5278 \cdot (10 + 15)) \quad (\$)$$

$$C_t = 9.45 \cdot 10^6 + 650 \cdot (0.22 \cdot 10^6 + 0.44 \cdot 10^6 + 0.13 \cdot 10^6) \quad (\$)$$

$$\boxed{C_t = 529 \cdot 10^6 \quad (\$)}$$

Plant capacity

$$P_{capacity} = 33297 \cdot 10^{-6} \cdot N_{turbine} \cdot D_{turbine}{}^{2} \cdot h_{rated}{}^{3/2} \cdot \eta_{turbine} \quad \text{(MW)}$$

For Two-way generation the following values were derived: h_{rated}=0.42R and $\eta_{turbine}$ = 0.85. Then:

$$\boxed{P_{capacity} = 33297 \cdot 10^{-6} \cdot 26 \cdot 5^{2} \cdot (0.42 \cdot 10)^{3/2} \cdot 0.85 = 186 \quad \text{(MW)}}$$

Total mean power output

The mean power output can be calculated by:

$$P_{t,mean/T} = \frac{33297 \cdot 10^{-6} \cdot N_{turbine} \cdot D_{turbine}{}^{2} \cdot h_{mean,netto}{}^{3/2} \cdot T_{t,generation} \cdot \eta_{turbine}}{T} \quad \text{(MW)}$$

For Two-way generation the following values were derived: h_{mean}=0.39R and $T_{t,generation}$ = 0.66T. Then:

$$P_{t,mean/T} = 33297 \cdot 10^{-6} \cdot 26 \cdot 5^{2} \cdot ((0.39 \cdot 10) \cdot 0.85)^{3/2} \cdot 0.85 \cdot 0.66 = 73 \quad \text{(MW)}$$

D Generic Plant Design Guideline

Procedure 1: Determine optimum turbine diameter and turbine number

If $H_{sea,MLWS} \geq 18.4$ then $D_{turbine} = 8$

Else $D_{turbine} = \dfrac{H_{sea,MLWS}}{2.3}$

Where;

$H_{sea,MLWS}$ = water depth at sea at MLWS (m)

$D_{turbine}$ = turbine diameter (m)

Input data:

$H_{sea,MLWS}$	=	m

Procedure 2: Determine optimum number of turbines

In case of One-way generation:

$$N_{turbine} = \frac{0.63 \cdot A_{bas,0} \cdot \sqrt{R}}{T \cdot D_{turbine}^{2}}$$

In case of Two-way generation:

$$N_{turbine} = \frac{0.92 \cdot A_{bas,0} \cdot \sqrt{R}}{T \cdot D_{turbine}^{2}}$$

Where:

$N_{turbine}$ = number of turbines (-)

$A_{bas,0}$ = basin surface area at MSL (m2)

R = mean tidal range (MHW-MLW) (m)

T = tidal period (s)

Input data:

$A_{bas,0}$	=	m	T	=	s
R	=	m			

Procedure 3: Check available barrage length

If $L_{barrage} \geq 4.55 \cdot N_{turbine} \cdot D_{turbine}$ then continue with Procedure 4

Else Decrease the number of turbines until it meets with the barrage length condition

Where:

$L_{barrage}$ = barrage length (m)

Input data:

$L_{barrage}$	=	m

Procedure 4: Determine the required (starting) head difference

$$h_{req} = 0.28\,R$$

Where;

h_{req} = required head difference (m)

Input data:

R = m

Procedure 5: Determine the generator capacity

$$P_{rated} = 33297 \cdot 10^{-6} \cdot D_{turbine}^{\ 2} \cdot h_{rated}^{\ 3/2} \cdot \eta_{turbine}$$

	h_{rated}	$\eta_{turbine}$
One-way generation	$0.51R$	0.89
Two-way generation	$0.42R$	0.85

Total plant capacity can be calculated by multiplying P_{rated} with $N_{turbine}$.

Where;

P_{rated} = rated power (= generator capacity) (MW)

ρ = water density (kg/m3)

g = gravitational acceleration (m/s2)

h_{rated} = rated head difference (m)

$\eta_{turbine}$ = averaged turbine efficiency (-)

η_{g} = averaged generator efficiency (-)

Input data:

ρ = kg/m^3

Procedure 6: Determine sluice gate surface area

$$A_{t,s} = \tfrac{1}{2} \cdot \pi \cdot D_{turbine}^{\ 2} \cdot N_{turbine}$$

Where;

$A_{t,s}$ = total sluice gate surface area (m2)

Procedure 7: Determine total mean power output

$$P_{t,mean/T} = \frac{33297 \cdot 10^{-6} \cdot N_{turbine} \cdot D_{turbine}^{\ 2} \cdot h_{mean}^{\ 3/2} \cdot T_{t,generation} \cdot \eta_{turbine}}{T}$$

	h_{mean}	$T_{t,generation}$	$\eta_{turbine}$
One-way generation	$0.46R$	$0.38T$	0.89
Two-way generation	$0.39R$	$0.66T$	0.85

Where;

$P_{t,mean/T}$ = mean power output per tidal period (MW)

h_{mean} = mean head difference (m)

E Generic Site Selection Guideline

Procedure 1: Check tidal power feasibility criterion

If	$R \geq 7$	then	Continue with Procedure 2
Else			**Site is not economic attractive for tidal power**

Where;

R	= mean tidal range (MHW-MLW) (m)

Input data:

R	=	m

Procedure 2: Determine tidal power feasibility number κ_1 by three ratios

$$\kappa_1 = r_{grid} + \cdot r_d + \cdot r_l$$

With;

$$r_{grid} = \frac{s_{grid} \cdot T}{10 \cdot A_{bas,0} \cdot R^2 \cdot \left(\frac{R + H_{bas,mean,scheme}}{R}\right)^{\sqrt{\frac{4 \cdot A_{bas,MHW}}{3 \cdot A_{bas,0}} - \frac{4}{3}}}}$$

$$r_d = \frac{H_{w,mean}{}^2}{9 \cdot R^2}$$

$$r_l = \frac{L_{barrage}}{3.54 \cdot \sqrt{A_0}}$$

Where;

κ_1	= interim feasiblity number (-)
r_{grid}	= grid distance ratio (-)
r_d	= depth ratio (-)
r_l	= barrage length ratio (-)
s_{grid}	= distance to grid (m)
T	= tidal period (s)
$A_{bas,0}$	= basin surface area at MSL (m2)
$H_{bas,mean,scheme}$	= water depth at mean basin level, derived from generation scheme (m)
$A_{bas,MHW}$	= basin surface area at MHW (m2)
$H_{w,mean}$	= mean water depth at barrage (m)
$L_{barrage}$	= barrage length (m)

Input data:

s_{grid}	=	m	$H_{bas,mean,scheme}$	=	m
T	=	s	$A_{bas,MHW}$	=	m^2
$A_{bas,0}$	=	m^2	$H_{w,mean}$	=	m
R	=	m	$L_{barrage}$	=	m

Procedure 4: Determine the cost-power ratio r_{costs} for the selected site

$$r_{\cos ts} = \frac{C_t \cdot T \cdot 10^6}{5037 \cdot A_{bas,0} \cdot R^2 \cdot \left(\frac{R + H_{bas,mean,scheme}}{R}\right)^{\sqrt{\frac{4 \cdot A_{bas,MHW}}{3 \cdot A_{bas,0}} - \frac{4}{3}}}}$$

	$H_{bas,mean,scheme}$
Two-way generation	0.04*R*

With;

$$C_t = C_p + C_{turbine+g} + C_s + C_{dam} + C_{bottom} + C_{trans}$$

With;

$$C_p = 416 \cdot N_{turbine} \cdot 20.2 \cdot D_{turbine}{}^2 \cdot (R_{MHWS-MLWS} + 2 \cdot H_{wave,sign} + 2.3 \cdot D_{turbine})$$

$$C_{turbine+g} \approx 1.5 \cdot (6.3 \cdot 10^6 + 207 \cdot 10^3 \cdot \sqrt[4]{h_{rated}} \cdot N_{turbine} \cdot D_{turbine}{}^2)$$

$$C_s = 5278 \cdot N_{turbine} \cdot D_{turbine}{}^2 \cdot H_c$$

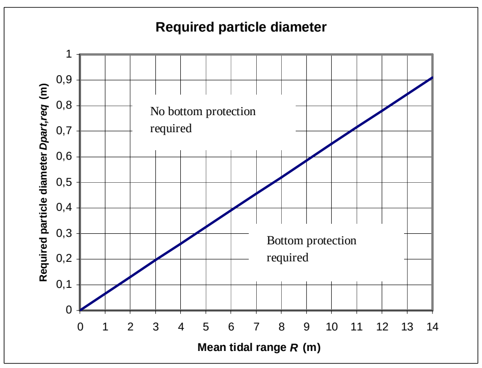
$$C_{dam} = 19 \cdot (L_{barrage} - 4.4 \cdot D_{turbine} \cdot N_{turbine}) \cdot (10 \cdot H_c + 1.75 \cdot H_c{}^2)$$

$$H_c = H_{sea,0} + 0.5 \cdot R_{MHWS-MLWS} + 2 \cdot H_{wave,sign}$$

$$C_{bottom} = 3800 \cdot D_{part,req} \cdot (L_p + L_s)$$

$$C_{trans} = 140 \cdot s_{grid}$$

$D_{part,req}$ can be derived by the following diagram:



Where;

r_{costs} = cost per power ratio (-)

C_t = total construction costs ($)

C_p = construction costs for powerhouses ($)

Continuation Procedure 4

$C_{turbine+g}$	= construction costs for turbines and generators ($)
C_s	= construction costs for sluice gates ($)
C_{dam}	= construction costs for dam ($)
C_{bottom}	= construction costs for bottom protection ($)
C_{trans}	= construction costs for transmission lines ($)
$N_{turbine}$	= number of turbines (-)
$D_{turbine}$	= turbine diameter (m)
$R_{MHWS\text{-}MLWS}$	= mean spring tidal range (m)
$H_{wave,sign}$	= significant wave height (m)
h_{rated}	= rated head difference (m)
H_c	= construction height (m)
$D_{part,req}$	= required particle diameter to withstand flow velocities (m)
L_p	= total powerhouse length (m)
L_s	= total sluice gates length (m)
$H_{sea,MLWS}$	= water depth at sea level at MLWS (m)

Input data:

T	=	s	$N_{turbine}$	=	
$A_{bas,0}$	=	m^2	$D_{turbine}$	=	m
R	=	m	$L_{barrage}$	=	m
$H_{wave,sign}$	=	m	L_p	=	m
$H_{bas,mean,scheme}$	=	m	L_s	=	m
$A_{bas,MHW}$	=	m^2	s_{grid}	=	m
$R_{MHWS\text{-}MLWS}$	=	m	$H_{sea,MLWS}$	=	m

Procedure 5: Final site selection

$$\kappa_2 = \kappa_1 \cdot r_{\text{costs}}$$

The site with the lowest obtained value can be characterized as the most promising site within the search area.