# Master thesis

# TIDAL POWER:

## Economic and Technological assessment

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## ABSTRACT

At present time there is concern over global climate change, as well as a growing awareness on worldwide population about the need on reducing greenhouse gas emissions. This in fact, has led to an increase in power generation from renewable sources. Tidal energy has the potential to play a valuable role in a sustainable energy future. Its main advantage over other renewable sources is its predictability; tides can be predicted years in advanced. The energy extracted from the tides can come from both, the vertical movements of the water associated with the rise and fall, potential energy, and from the kinetic energy, namely, tidal currents. A tidal barrage harnesses the potential energy while tidal stream turbines capture the energy from tidal currents.

This thesis reviews the physical principles of tidal energy considering gravitational effects of sun and moon; semidiurnal, diurnal and mixed tides, and periodic phenomena that affect tidal range. Moreover, an up-to-date review of the status of tidal energy technology is included. Furthermore, the different tidal conversion systems are introduced, tidal barrage and tidal stream turbines. The current issues for both technologies are presented, aiming to place the reader on the current situation.

The thesis also contains an economic assessment, where the current costs of both technologies as well as an estimation of the future costs are shown. The levelised costs of energy (LCOE), which measure the cost of the generated electricity, are also calculated and compared. From this chapter it is concluded, that although tidal current has very high costs, it has a clear potential to become competitive with other generation forms in the future as costs will considerably decrease as the installed capacity increases. On the other hand it is said that although tidal barrage is a mature technology has very high costs, however its deployment can bring several benefits. Finally a technological report is included. The purpose of it is to identify which technology, one direction or two-direction turbines, can generate more electricity under the same operating conditions. It also includes a cost analysis of both types of devices. The conclusion raised considering the electricity generated as well as the technology costs is that bi-directional devices have lower energy costs.

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# 1. Introduction

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Global energy requirements are mainly provided by the combustion of fossils fuel. The consequence of this heavy dependence is becoming an increasing concerning since fossils fuels have limited potential.  It is expected that due to the current rate of exploitation these resources will deplete within the coming decades.

The $CO_2$ released into the atmosphere from burning fossils fuels restricts the earth from radiating the heat from the sun back into space, resulting in a rise in global temperature.  Lately, there has also been an increase exploitation of coal and nuclear energy to ease the oil dependence, which has resulted in acid rain and public concern over nuclear waste. For this reason, every time more, policy makers and the population worldwide are becoming more aware of the need to reduce greenhouse emissions, in particular from the electricity industry.

Renewable energies technologies are becoming an increasing favorable alternative to tackle the climate change issue. Since renewable energy technologies are indigenous and non-polluting, they can cope with both security of supply concern and environmental issues [1]

There are several sources of renewable energy, such as wind, solar, wave and tidal, which exhibit a variable output, in other words, the output depends on weather conditions which cannot be controlled. As well as being weather dependent, many renewable technologies also face the challenge of being relatively unpredictable. [2]

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The development of these technologies is strongly influenced by energy policies. For instance, as solar and wind energy technologies have gained the greatest attention recently, they have experienced a considerable development.

Oceans which cover more than 70% of the earth have been appreciated as a vast renewable energy source. It is an emerging industry that has a potential to satisfy world-wide demand for electricity. Nowadays, there are several techniques for extracting energy from the sea, among which are tidal energy conversion techniques. [3]

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Tidal energy offers an immense and reliable source of energy. The total energy flux of the tides is about 3 TW, however only a small fraction of this potential would be harnessed on the foreseeable future. This is due to the fact that the energy is spread over a wide area, and what is more, often it is found in remote areas of consumption points.

Tidal generation has a significant advantage over many other forms of renewable generation as it is almost perfectly predicted over long time horizons. Therefore, incorporating tidal generation into the system should be less challenging than other forms of renewable generation which are highly unpredictable.

Harnessing tidal energy from the rise and fall of the tides has been exploited up to a commercial scale using tidal barrage systems. On the other hand, great efforts to exploit the kinetic energy from tidal currents have been directed. This technology remains fifteen years behind the wind technology industry. However, tidal current industry can benefit from the advances in technology and engineering resulted from the wind industry. [4]

This thesis is constituted by four different sections. Section one presents a detailed explanation of tidal power, including the physics of tidal energy, as well as the existing technologies and the different operating modes they can operate. Chapter two includes the current issues and the future development of tidal energy technologies. Following that, in section three an economic assessment is carried out. The aim of it is to determinate the costs involved in developing tidal barrage and tidal current technologies, estimating future costs for both technologies as well as the potential of them. Finally, a technological study of tidal barrage devices, one-direction and bi-directional turbines, is included in section four.

## 2. Physical principle of tidal energy

Tidal power, sometimes called tidal energy, is the energy dissipated by tidal movements which directly derives from the interaction of the gravitational forces between the seas and the primary astronomical bodies of our system [5]. A tide is a regular rise and fall of the surface of the ocean due to the gravitational force of the sun and moon on the earth and the centrifugal force produced by the rotation of the earth and moon about each other. It is known that the gravitational force that mutually attracts any two bodies is directly proportional to the product of their masses and is inversely proportional to the square of the distance that separates the masses. The attractive force exerted by the sun or moon on a molecule of water can be calculated as:

$$\boldsymbol{F} = \frac{\boldsymbol{K\ x\ M\ x\ m}}{\boldsymbol{d^2}} \qquad \text{Eq. 2.1}$$

*F*: attraction force

K: universal constant of gravitation

M: mass of the moon or sun

m: mass of a water molecule

d: the distance from a water molecule to the moon/sun

The effect of the gravitational force exerted by the moon on the earth is about 2.17 times larger than the exerted by the sun, due to the smaller distance between the earth and the moon [6]. A bulge of water is created being greater on the earth side nearest to the moon due to the gravitational force. Simultaneously, another bulge of water is created due to the centrifugal pull due to the rotation of the earth-moon system, but in this case the water bulge is created on the side of the earth furthest away of the moon. As a result of the two forces, a resultant bulge is created around the earth as it is illustrated in *Fig 2.1*.

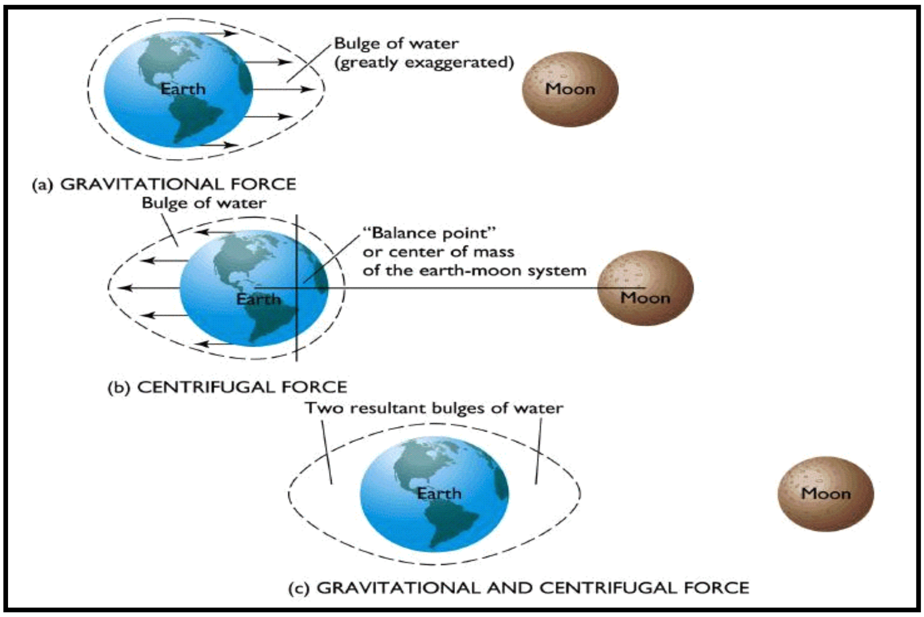


**Fig. 2.1.** Interaction between earth and moon[I].

When sun and moon are in line whether pulling on the same side or on the opposite side (full or new moons) the gravitational attraction combine together causes high tides, known as spring tides. Conversely, when sun and moon are orthogonal, their gravitational forces pulls water in different directions causing the bulges to cancel each other, giving place to neap tides. The maximum power is produced during spring tide while the minimum is during the neap tide.

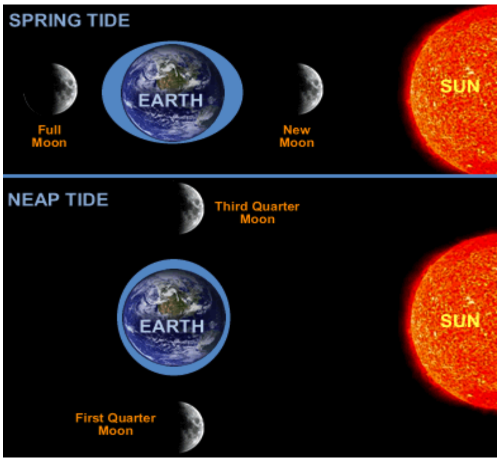


**Fig. 2.2.** Sun and moon interaction with the earth [II]

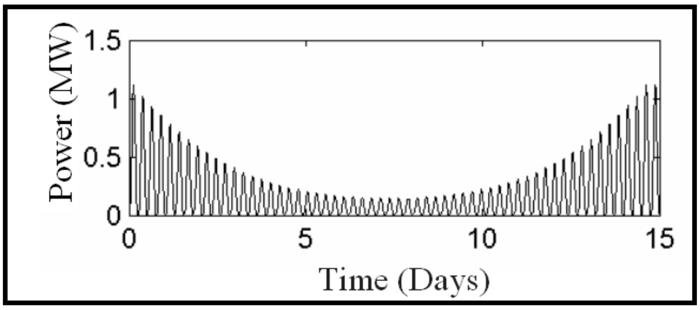


**Fig. 2.3.** Tidal power over the spring-neap cycle[III].

Tidal phenomenon is periodic. The periodicity varies according to the lunar and solar gravitational effects, respective movements of the moon and sun, and other geographical peculiarities. The mean interval between conjunctions of the sun and moon (new moon to new moon) has a cycle of 29.53 days, which is known as Synodic month or lunation. There are three different types of tidal phenomena at different locations of the earth [7].

### A. <u>Semidiurnal tides with monthly variation.</u>

This type of tide has a period of 12h 25 min, due to the earth rotation relative to both sun and moon, consequently the tidal phenomenon occurs twice every 24h 50min 28s [8], so each landmass is exposed to two high tides and two low tides during each period of rotation [9], as it is shown in *Fig 2.4.*. The amplitude of the tide varies according to the lunar month, with higher tidal range at full moon and new moon, when sun and moon are aligned. Neap tides occur during half-moon as the resultant gravitational pull is minimum. However, as is shown in *Fig 2.4.* , one of the tides has greater range than the other, having a higher high and a lower low, therefore, a greater tidal flow while water is coming in and going out during the period between high and low level. Furthermore, the tidal output peaks and troughs four times a day as the tide comes in and out twice daily *Fig 2.5.* .

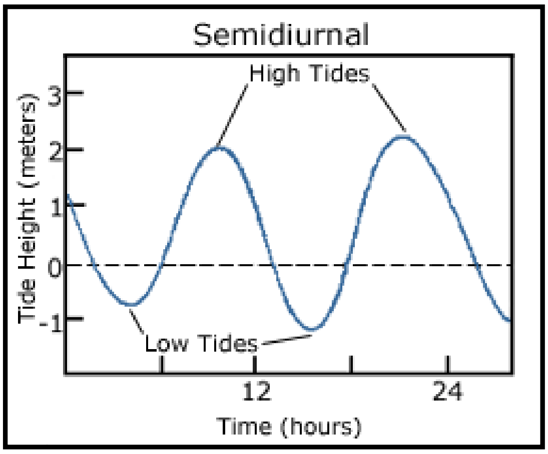


**Fig. 2.4.** Semidiurnal tide[IV]

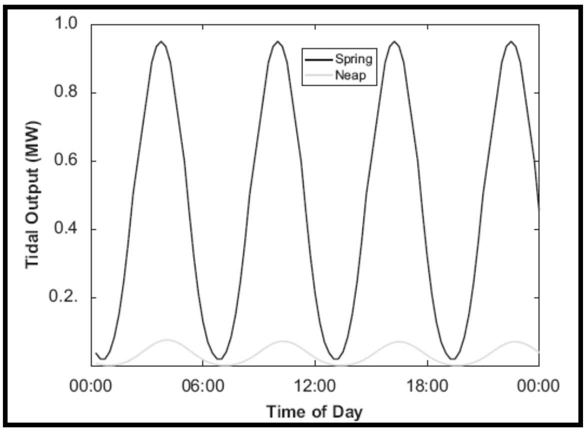


**Fig. 2.5.** Power output during spring and neap tide [III].

**B. Diurnal tides with monthly variation**

This type of tide is found in China Sea and Tahiti. In this case, the tidal period is of 24h 50 min 28s, a full revolution of the moon around the earth. During each earth rotation, a point of the earth surface will pass through different parts of the equilibrium tide envelope and therefore experience a diurnal variation in tide levels. [7]

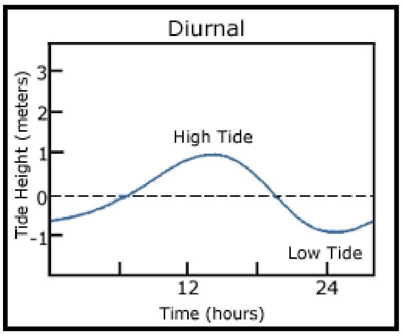


**Fig. 2.6.** Diurnal tides [IV]

**C. Mixed tides**

This type of tides combines the characteristics of diurnal and semidiurnal tides. Moreover, they can also display monthly and bimonthly variation. They are found in the Mediterranean Sea and at Saigon.

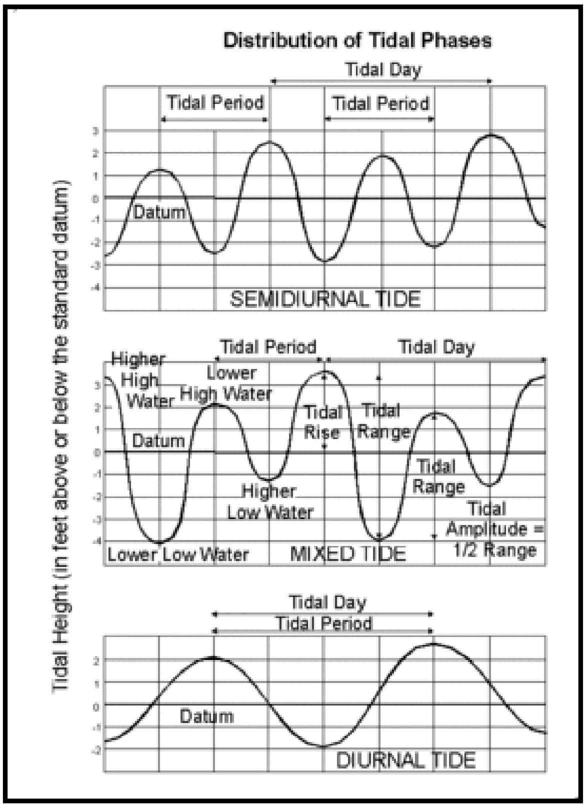


**Fig. 2.7.** Type of tides[V]

There are several periodic phenomena that affect on tidal behavior. The following mentioned are the ones which have greater impact.

- A **14-day cycle**, due to the interaction of the gravitational field of the sun and moon. As a result of the moon's elliptical orbit the cycle is slightly modified, so successive spring-neap tides can vary in amplitude by about a 15%.
- A **half year cycle**, as a result of the moon's orbit inclination giving place to a 178 days period between the highest spring tides, which take place in March and September.
- The **Saros**, period of 223 synodic periods equivalent to 18 years and 10 days, is the time required by the earth, sun and moon to return to the same relative positions.

Tidal currents occur in coastal areas and in places where the seabed forces the water through relatively narrow boundaries. Thus both high tidal ranges and narrow channels are generally required to cause significant tidal stream currents. The range of a spring tide is commonly about twice the neap tide range. The common tidal range is about 50 centimeters in the open ocean [6]. However, the tidal amplitude can be increased by several local effects such as shelving, funneling, reflection and resonance. The shelving effect consists on increasing the deep water tidal wave height as the wave slows down when entering in shallow water areas. The tidal amplitude can be further increased due to funneling effect, which occurs when the tidal bulge progresses into a narrowing estuary. Moreover, tidal wave can also be reinforced by reflections of the waves by the coastline. At some sites, the tidal flow can be heightened to more than 10 meters by resonance effects, i.e. Bay of Fundy, in Canada, where the greatest tides in the world can be found, and the Severn Estuary in England. The resonance effect it takes place when the tide at the mouth of the estuary can resonate with the natural frequency of tidal propagation up the estuary. [7]

Tidal currents can flow in two directions; the current moving in the direction of the coast is known as flood current and the current receding from the coast is known as ebb current. The current speed varies from zero to a maximum. The zero current speed occurs between the ebb and the flood current, slack period; while the maximum speed is reached halfway between the slack periods. [10]

All tidal variations rise and fall and flood and ebb current can be utilized to generate electricity. The generation of electrical power from ocean tides is very similar to hydroelectric generation.

## 3. State of the art

Tidal energy is one of the oldest forms of energy used by humans. Indeed, the earliest evidence of the use of the oceans' tides for power conversion dates back to about 900 A.D., but it is likely that there were predecessors lost in the anonymity of prehistory. [6]

Much later, American colonists built tidal-powered mills in New England. Tide mills consisted of a storage pond, filled by the incoming (flood) tide trough a sluice and emptied during the outgoing (ebb) tide through a waterwheel. The tides turned waterwheels producing mechanical power to mill grain, the power was available during two to three hours, usually twice a day [11].

The idea of generating electric power from exploiting the power of the tides in estuaries was proposed in 1920 in UK. In 1967, the world's first tidal electric plant was successfully completed on the **Rance** Estuary in Brittany, France. This 240MW power plant is sufficient to power 4% of the homes in Brittany. So far it is still the largest operating commercial tidal facility in the world. It attracts hundreds of thousands of visitors every year. The 720 meter long barrage which encloses a surface area of the estuary of 22 $km^2$ is simultaneously used as a road and it also contains a ship lock. The barrage contains 24 reversible 10 MW bulb turbines, operating with a hydrostatic head of 5m. The mode of operation of La Rance is a combination of two-way generation and pumped storage. Pumping from the sea to the basin is carried out at certain tides to enhance generation on the ebb. The plant produces a net power output of approximately 480 GWh per year. After La Rance tidal power construction, tidal power has been exploited on a significant scale.

The second commercial-scale tidal dam was the **Annapolis Royal Generating Station** tidal power, located in Bay of Fundy, Canada, which was constructed between 1980 and 1984. Its construction was a government pilot project to explore the potential of harnessing tidal energy [12]. Annapolis tidal power has a 20 MW capacity, which is connected to the national grid. It only uses one turbine, the largest Straflo (rim) turbine in operation in the world, producing 30GWh of electricity per year. This 20-megawatt turbine had some difficulties with clogging seals necessitating two forced outages, but has been working without interruption since its early days.

In the Soviet Union, **Kislaya Guba** power facility on the Barents Sea was constructed in 1968 as a government pilot project, with a generating capacity of 0.4 MW, but in 2006 it was upgraded with a 1.2 MW experimental advanced orthogonal turbine. Kislaya Guba is the smallest tidal power facility in operation worldwide [13].

Following that, **Jiangxia Tidal Power Station** was built in the south of Hangzhou, China, operational since 1985 and with and installed capacity of 3.9 MW. The plant operates in a two-way mode [7]. It is the largest tidal power plant in China and the third largest tidal power plant in the world. Besides that, 7 more tidal power plants are deployed around the country.

Currently, there are several tidal power plants underdevelopment as well as many studies going on concerning tidal power resources where future plants can be constructed. On the following paragraphs there is a brief description of some of them.

In May 2009 the first MW was installed in **Jindo Uldolmok Tidal Power Plant**, moreover, a tidal scheme is planned to be expanded to 90 MW of capacity by 2013.

**Sihwa Lake Tidal Power Plant,** a 254 MW tidal plant in South Korea which is under construction.

The Indian state of Guajart is planning to host South Asia's first commercial-scale tidal power station. The company Atlantis Resources plans to install a 50MW **Tidal farm in the Gulf of Kutch** on India's west coast, with construction starting early in 2012. [15]

The contract for an 812 MW **tidal barrage** near **Ganghwa Island** north-west of Incheon has been signed by Daewoo. Completion is planned for 2015.

The Korean government has proposed building a 1,320 MW **barrage around the islands at west of Incheon** with projected construction start in 2017. There are other South Korean projects which include **barrages** planned for Garorim Bay, Ansanman and Swaseongho. The barrages are all in the multiple-hundred megawatts range.

To sum up, on *Table 3.1.* the major world tidal barrage sites are shown, some of them have already been developed while others still under feasibility studies such as the Severn Estuary in the UK, Bay of Fundy in Canada, Mezeh Bay and Tugar Bay in Russia. Moreover, in addition to these large sites there are numerous small scales sites such as estuaries and rivers that could be utilized. The small scale sites of interest include Garlolim Bay in Korea, the Gulf of Kachchh in India, Secure Bay in Australia and Sao Luis in Brazil.

| Location | Mean range (m) | Basin Area ($km^2$) | Potential mean power (MW) | Potential annual production (GWh/year) |
|---|---|---|---|---|
| North America | | | | |
| - Passamaquoddy | 5.5 | 262 | 1800 | 15800 |
| - Cobscook | 5.5 | 106 | 722 | 6330 |
| - Bay of Fundy | 6.4 | 83 | 765 | 6710 |
| - Minas-Cobequid | 10.7 | 777 | 19900 | 175000 |
| - Amherst point | 10.7 | 10 | 256 | 2250 |
| - Shepody | 9.8 | 117 | 520 | 22100 |
| - Cumberland | 10.1 | 73 | 1680 | 14700 |
| - Petitcodiac | 10.7 | 31 | 794 | 6960 |
| - Memramcook | 10.7 | 23 | 590 | 5170 |
| South America | | | | |
| - San Jose, Argentina | 5.9 | 750 | 5870 | 51500 |
| United Kingdom | | | | |
| - Severn | 9.8 | 70 | 1680 | 15000 |
| - Mersey | 6.5 | 7 | 130 | 1300 |
| - Solway Firth | 5.5 | 60 | 1200 | 10000 |
| - Thames | 4.2 | 40 | 230 | 1400 |
| France | | | | |
| - Aber-Benoit | 5.2 | 2.9 | 18 | 158 |
| - Aber-Wrac'h | 5 | 1.1 | 6 | 53 |
| - Arguenon | 8.4 | 28 | 446 | 3910 |
| - Fremaye | 7.4 | 12 | 148 | 1300 |
| - La Rance | 8.4 | 22 | 349 | 3060 |
| Ireland | | | | |
| - Strangford Lough | 3.6 | 125 | 350 | 3070 |

| | | | | |
|---|---|---|---|---|
| Russia | | | | |
| - **Kislaya** | 2.4 | 2 | 2 | 22 |
| - **Lumbouskii Bay** | 4.2 | 70 | 277 | 2430 |
| - **White Sea** | 5.65 | 2000 | 14400 | 126000 |
| - **Mezen Estuary** | 6.6 | 140 | 370 | 12000 |
| Australia | | | | |
| - **Kimberley** | 6.4 | 600 | 630 | 5600 |
| **China** | | | | |
| - **Baishakou** | 2.4 | No data | No data | No data |
| - **Jiangxia** | 7.1 | 2 | No data | no data |
| - **Xinfuyang** | 4.5 | No data | No data | No data |

**Table 3.1.** Major world tidal barrage sites [I].

On the other hand, recent studies indicate that marine currents have the potential to supply a significant fraction of future electricity needs. The potential of the European resource is estimated to exceed 12,000 MW of installed capacity [16]. Locations with especially intense currents are found around the British Islands and Ireland, between the Channel Islands and France, in various channels between the Greek islands and the Aegean, in the Straits of Messina between Italy and Sicily. Other large marine current resources can be found in regions such as South East Asia, in both east and west coast of Canada and certainly in many other places around the Globe that require further investigation. However, not much deployment has been carried out up to the date. Tidal current technology has not reached its maturity, so commercial stage is not yet achieved. Several studies have been translated into down-scale models and full-scale prototypes, and also the first dedicated test center, The European Marine Energy Center (EMEC), has been founded. This center was set up to offer the developers the opportunity to test full-scale prototype devices in real marine energy conditions [17].

Last but not least, it is worth mentioning that global tidal range energy potential is estimated to be about 3 TW, around 1 TW is available at shallow waters. The energy extracted is proportional to the tidal amplitude squared, so therefore, sites with large tidal amplitudes are the best suited for tidal power developments.

# 4. Tidal energy conversion system

The energy extracted from the tides can be obtained from both, the vertical water movements associated with the rise and fall of the tides, potential energy or the kinetic power, which is the result of the roughly horizontal water motions termed as tidal currents. For these reason, tidal power facilities can be categorized into two main types: tidal barrages and tidal current turbines.

## 4.1. Tidal barrages

Tidal barrages use the potential energy of the tides to generate electricity. Given a basin, the theoretical potential energy can be calculated as:

$$\mathbf{E = g\rho A \int zdz = 0.5g\rho Ah^2} \qquad \text{Eq. 4.1}$$

Being:

- $E$: energy (Joule)
- $g$: acceleration of gravity (9.8 $m/s^2$).
- $\rho$: seawater density (approximately 1022 $kg/m^3$),
- $A$: sea area ($m^2$),
- $z$: vertical coordinate of the ocean surface (m)
- $h$: tide amplitude (m).

Note: for seawater: $(g\rho)$ = 10.0156 $kNm^{-3}$ [7]

The technology required to convert tidal range into electricity is very similar to conventional hydroelectric power plants, but in this case, the current flows in both directions. [4]. This means, that tidal barrages are unable to produce electricity at a constant rate, as they have to wait for sufficient hydrostatic head between both sides of the dam. However, electricity production from tidal barrages is totally predictable allowing for ease of electricity suppliers.

A tidal barrage is generally a dam placed across an estuary that experiences a tidal range of 5m [18]. The basic elements that constituted a tidal barrage are turbines, sluices gates, embankments, caissons and ship locks. Caissons, very large concrete blocks, house sluices, turbines and ship lock; any section of the barrage not containing sluices or turbines may be completed using blank caissons. The dam can either be placed at the entrance of channels where ocean water gets inside the land via a bay or between the main land and an island or just in between two islands. Embankments function is to seal the basin, where it is no sealed by caissons. The sluices open when there is an adequate difference in the water elevation on both sides of the barrage; the hydrostatic head that is created causes the water flow through the turbines, turning an electric generator to produce electricity.

When deploying a tidal barrage, technical evaluation of the following aspects will be necessary before the final form of the project is decided [7]:

- Type of structure: single basin or double basin
- Dam and plant location
- Operating mode: single or double action with or without pumping
- Unit power of turbines and generators
- Total power output

There are two main types of tidal barrages: single-basin system and double-basin system which their main difference relies on the number of basins.

## ■ <u>SINGLE BASIN TIDAL BARRAGE</u>

This system consists of one basin and requires a barrage across an estuary or a bay. There are three main operation patterns in which power can be generated within a single basin: ebb generation, flood generation and two- way generation [19].

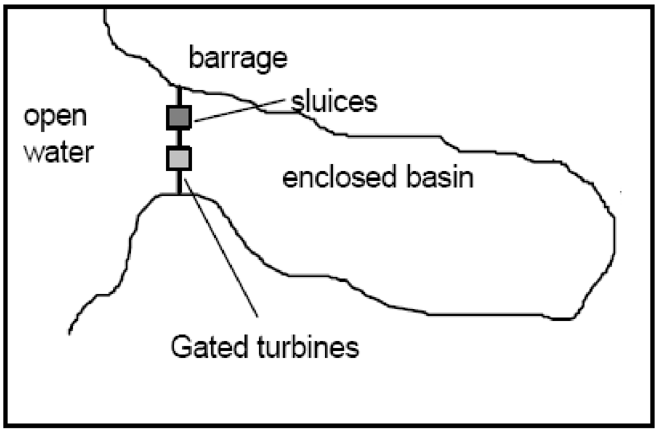


**Fig. 4.1.** Hypothetical one-basin system [VI]

- **Ebb generation**: This method is the simplest mode of operation for a tidal plant, in which the basin is filled with water through the sluices gates during flood tide. At high tide, the sluice gates are closed, keeping the water in the basing. During periods of low demand, extra water can be pumped to raise the level further. The sluices are kept closed until the current has ebbed sufficiently to develop substantial hydrostatic head across the barrage [20]. Consequently, the water is let flow through the turbines, generating electricity for several hours, until the hydrostatic head drops to the minimum level in which turbines can efficiently operate [6]. Once this point is reached, the sluices are opened, turbines disconnected and the basin is filled again, starting a new cycle. Ebbs generation takes this name because generation occurs as the tide ebbs.

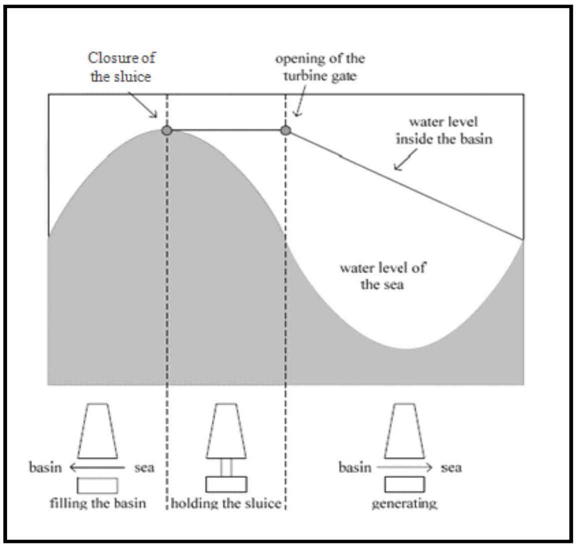


**Fig. 4.2.** Ebb generation mode [VII]

Following typical day fluctuations are summarized:

- Every day there are two burst of generation activity beginning approximately three hours after high tide and lasting 4 to 6 hours.

- For each tidal cycle production levels rapidly increase with tidal range. Therefore, the output characteristic displays a 14 days cycle.

- High water times shift by about 1 hour per day.

- For each 14 day, energy production will not be evenly distributed throughout the 24h of the day.

- Output levels will only show slight variation from one fortnightly period to the next.

- Annual production levels show fluctuations of around ±5% and follow a cycle of 18 2/3 years.

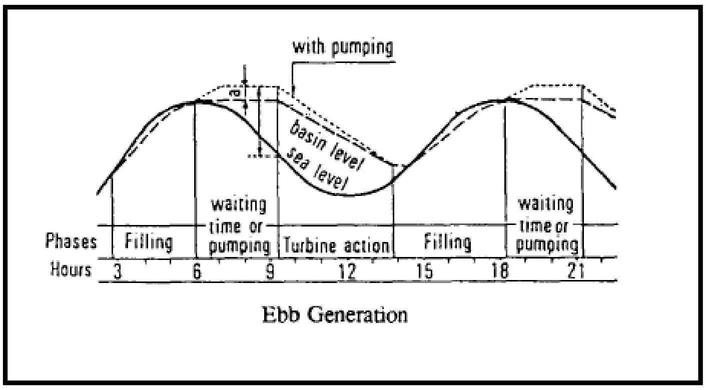


**Fig. 4.3.** Ebb generation mode [VIII]

- **Flood generation**:

The flood generation method uses incoming tide to generate power. During the flood tide turbines and sluices gates are kept closed until a substantial hydrostatic head is developed across the barrage. Once the sufficient head is achieved the turbine gates are opened allowing the water to flow through them into the basin.

Generally, flood generation is less efficient than ebb generation because the volume of water stored on the upper half of the basin (which is where ebb generation operates) is greater than the volume stored on the lower half (filled first during flood generation).Therefore, the water head between the basin and the sea, reduces more quickly than it would be with ebb generation, thus, less energy is produced.

Moreover, as in average the system it creates a decrease in sea level within the basin, it can have a negative effect on shipping and the environment; as the level of the reservoir is subjected to continuous changes in water level, whereas in ebb generation, the greater changes in water level are suffered by the basin.

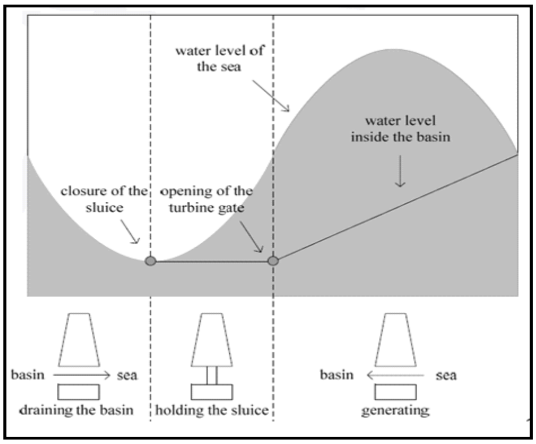


**Fig. 4.4.** Flood generation [VII]

- **<u>Two-way generation</u>**:

This method combines ebb generation and flood generation. Generation occurs in both, as the tide ebbs and floods in every cycle. The sluices gates are kept close until near the end of the flood cycle. When the minimum hydrostatic head for electricity generation is reached, the sluices gates are opened. At high tide, the sluices gates are closed and water is trapped until sufficient hydrostatic head is reached again. Water is then allowed to flow through the turbines to generate in the ebb mode. This method has an advantage respect to the other two, it has a reduced period of non-generation and a reduction in generators costs due to lower peak power [19]. Blocks of energy are produced in approximately 6 hours cycle, with smaller output and greater plant utilization factor [7]. However, it presents a smaller power output than for simple ebb generation, due to the reduce range within the basin. Moreover, turbines are designed to operate in both directions are more costly.

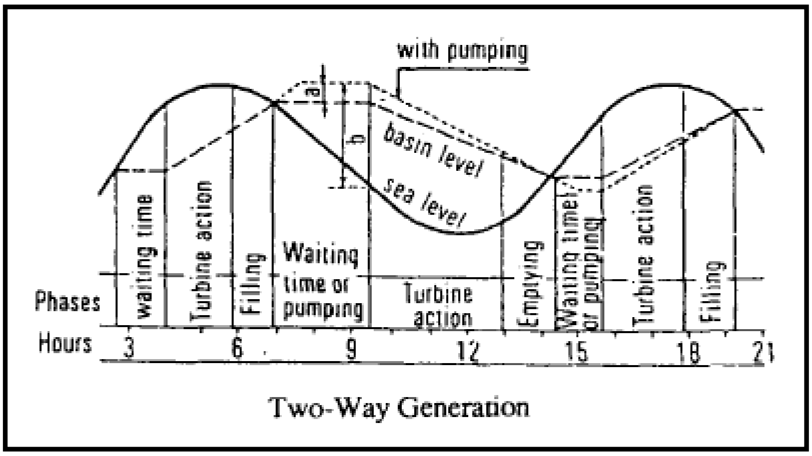


**Fig. 4.5.** Two-Way generation [VIII]

■ **DOUBLE BASIN-TIDAL BARRAGE**

This system requires the construction of two barrages, the main one and the inner one, giving place to two basins. The main basin is essentially the same as ebb generation in a single-basin system. The only difference is that in this case, part of the energy produced by it is used to pump water into the second basin [4]. For this reason, the second barrage acts as a storage element, extending the time period in which the barrage can produce electricity, therefore this system can adjust the delivery of electricity to match consumer demands. The system major advantage is the ability to delivery electricity at periods of high demand. However, double-basin systems are unlikely to become feasible for both, inefficiencies of low-head turbines and high construction costs.

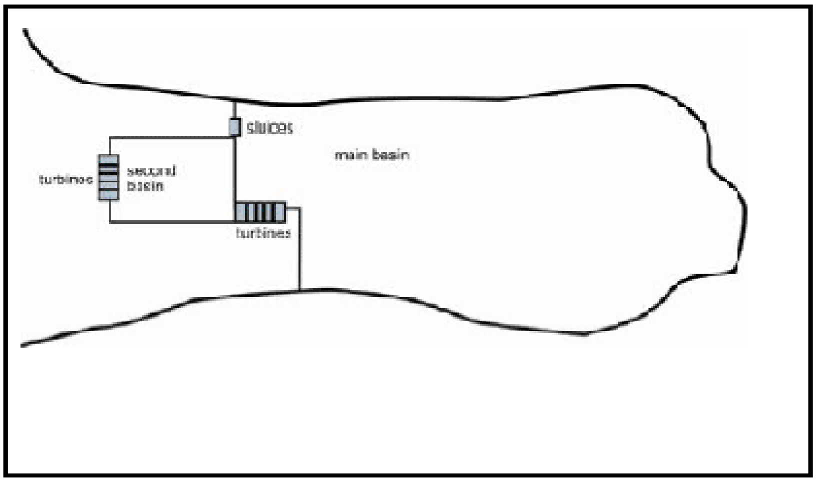


**Fig. 4.6.** Hypothetical two-basin system[VI]

### 4.1.1. Types of turbines

As previously commented, turbines are one of the main elements for electricity generation in tidal barrages. The turbine choice will determined the operation conditions and the environmental impact, for these reason several aspects such as, head variability, flow rate, requirements for pumping or continuous operation, requirements for two-way generation operation, start-stop frequency, etc. have to be considered. It is worth mentioning that due to the development in turbines design, routine repair is carried out with a greater ease, thus, maintenance is no longer consider a development issue.

Nowadays, there are several types of turbines available; the most commonly used are bulb, rim and tubular turbines.

- **Bulb turbines**

Bulb turbines are a type of hydro turbines, whose name comes from the shape of the upstream watertight casing which contains the generator located in the horizontal axis and is mounted inside the water passageway as an integral unit with the turbine. This installation can offer significant reductions in size, cost and civil work as there is a low need of excavation and what is more, the draft tube improves the hydraulic behavior of the bulb unit [21].

During its operation water floods around the turbine, its maintenance is difficult, as while it is carried out, water has to be prevented from flowing through the turbine [6]. This means that when inevitable maintenance of the turbine or/and the generator is needed, it has to be lifted off the water, and consequently, the turbine stops producing power for the duration of the process.

They are considered the most efficient solution for low heads up to 30 m, for these reason they are the most popular turbines among barrage designers. Moreover, the turbine and generator are reversible, namely, they can generate power on the flood tide or act as a motor to pump seawater into the basin. Bulb turbine has proved very reliable, as it has operated nearly constantly without majors problems for over 30 years in La Rance tidal barrage, France.

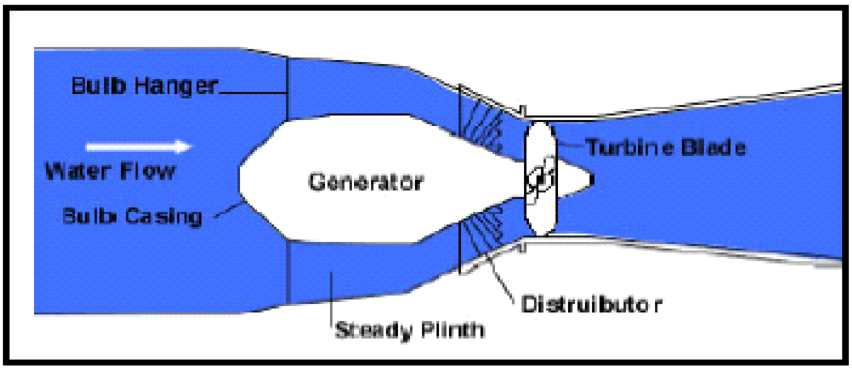


**Fig. 4.7.** Bulb turbine [VII]

- **Rim turbine**

Rim turbine's generator is separate from the turbine itself; it is mounted on the barrage and is connected through a shaft that moves with the turbine [22]; consequently, only the turbine is in water flow. Moreover, the rotor is protected from ingress of sea water by especially designed water seals.

Concerning maintenance, it is necessary to remove them when turbine maintenance is required, although the generator can be accessed when water inlet gate is closed and water drains off. As a result, the generator maintenance problem in bulb turbines is solved [6].

Early design were more suitable for river applications due to water seals leaking under pressure; however recent improvements have made them more reliable, there being a 20 MW Straflo turbine, 8.2 m diameter, currently installed in Annapolis River Tidal Barrage Canada.

This kind of turbine is preferred for its greater theoretical efficiency and greater inertia (to satisfy stability criteria). However, it can only operate on the ebb tide and cannot be used to pump storage to the basin due to their more-delicate nature.

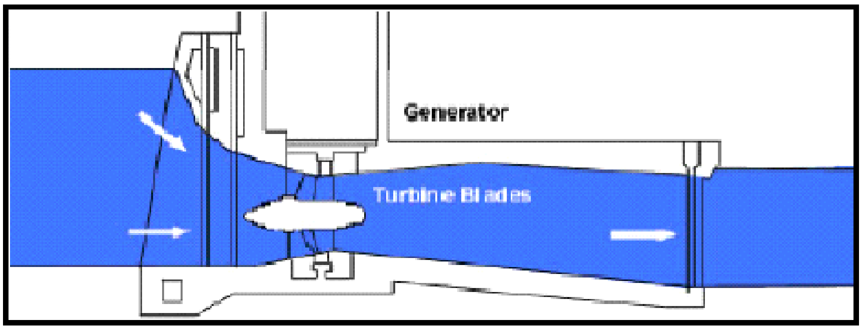


**Fig. 4.8.** Rim turbines [VII]

- **<u>Tubular turbines</u>**

In tubular turbines the generator is mounted on the top of the barrage at a 45 degree angle with the turbine, and the blades are connected to a long shaft.

The real advantage that they present is that the blades can be adjusted [22]. This means that they can be changed to meet electricity demand; smaller blades will generate less power while larger blades will generate more power. This allows the turbine to run more efficiently, generating only the amount of power needed. Furthermore, this design gives some room to a gearbox, which allows more efficient operation of generators. Furthermore, maintenance can take place in location as soon as water supply has been isolated. However, it presents some vibration problems of the long shaft and it cannot be reversed to operate on flood tide or used to pump storage.

Tubular turbines have been used in some hydro plants in US and they are proposed for the Severn tidal project in the United Kingdom [6].

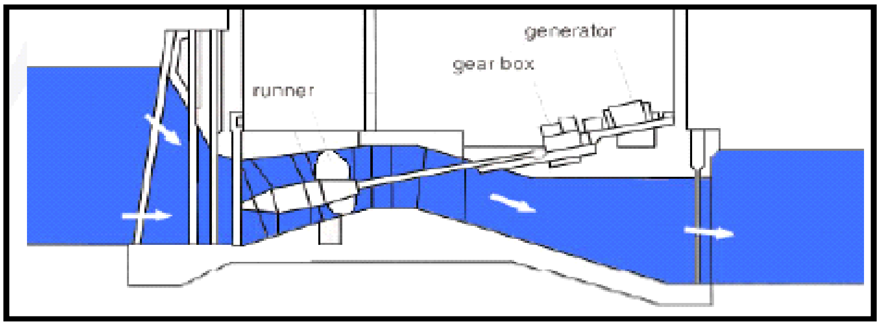


**Fig. 4.9.** Tubular turbines [VII]

## 4.2. Tidal current turbines

Tidal current turbines extract the kinetic energy from the moving unconstrained tidal streams to generate electricity. Currents have the same periodicity as vertical oscillations, being thus predictable, although they tend to follow an elliptical path.
The ideal kinetic energy is calculated as:

$$\mathbf{E = m\,V = \rho\,v\,V} \qquad \text{Eq. 4.2}$$

Where:

- m is the mass of water $m = \rho v$
- $\rho$ is the seawater density (approximately 1022 kg/m3)
- $v$ is the water volume

The ideal power for a mass of water passing through the rotor with a cross sectional area, A, can be expressed as it follows [6]:

$$\mathbf{P_T = 0,5\,\rho\,A\,V^3 C_p} \qquad \text{Eq. 4.3}$$

Being,

- $P_T$: power developed by the rotor (W)
- A: area swept out by the turbine rotor ($m^2$),
- V: stream velocity (m/s).
- Cp: power coefficient of the turbine, which is the percentage of power that the turbine can extract from the water flowing through it. According to the studies carried out by Betz, the theoretical maximum amount of power that can be extracted from a fluid flow (water or air) is about 59%, which is referred to Betz limit.

Tidal current technology extracts the kinetic energy in a similar way to harvest wind energy from air [23]. However, there are several differences in the operating conditions. Operating under similar conditions, water is 832 times denser than air, and the water flow speed generally is much smaller [24]. Due to the difference in density between both fluids, the power intensity in water currents is significantly higher than air streams. Consequently, water current turbine can be built considerably smaller than an equivalent powered turbine [25]. In contrast to atmospheric air flows, the availability of tidal currents can be predicted very accurately. Another specific advantage of tidal current devices is the limited environmental impact as their installation requires minimum land use, and fully submerged devices will not affect optically or acoustically their surroundings [16]. Finally, submerged marine current converters are considered to operate in safe environment, disturbances caused by extreme weather conditions are significantly attenuated to the depths of 20-30 m, where the devices will be generally placed. However, since tidal current turbines operate in water, they experience greater forces and moments than wind turbines. In addition, tidal current turbines must be able to generate during both, ebb and flood currents, and be able to withstand the structural loads when not generating electricity.

In the simplest form a tidal current turbine is constituted by a number of blades mounted on a hub, a gearbox and a generator. The hydrodynamic effect of the water when flowing through the blades causes the rotor to rotate, thus turning the generator to which the rotor is connected through the gearbox. The gearbox is used to transform the rotational speed of the rotor shaft to the desire input of the generator. The electricity produced is transmitted to land through cable.

Turbines are mounted to a support structure that is required to withstand the harsh environmental conditions. The choice of the foundation depends mainly on geographical conditions such as water depth, seabed conditions, streams etc. and the type of turbine to be installed. Moreover, it is an important aspect concerning feasibility and profitability of the devices. There are three main support structures. The first one, **gravity structure** consists on a big mass of concrete and steel, which is attached to the base of the structure to provide stability [25]. The second option is known as **piled structure** which is pinned to the seafloor using one or more steel or concrete beams. And finally, the third option is the **floating foundation**; its structure is usually moored to the seafloor using chains or wire. In this case, the turbine is fixed to a downward pointing vertical beam, which is fixed to a floating structure.

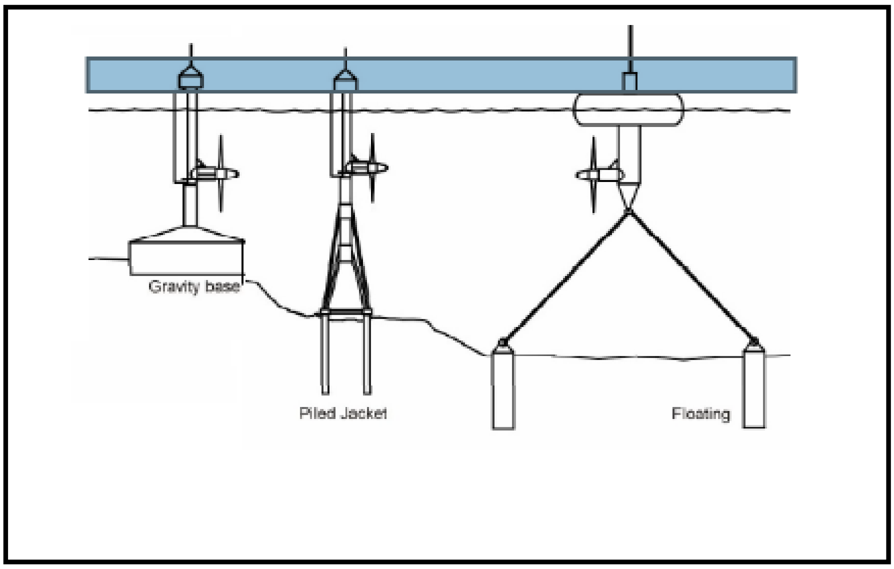


**Fig. 4.10** Type of foundations [IX]

As mentioned on *chapter 2*, the maximum power is only achieved for a few days per month during spring tide. For this reason, if a turbine was to be installed rated to capture the full energy potential during the spring tide, it would have a very load factor, less than 18%. Therefore, developers have tended to install turbines that are rated at a lower level than the maximum power available at a particular site. This is known as Electrical Down Rating (EDR), which is shown in *Fig. 4.11.* Tidal power over the spring-neap cycle[2].

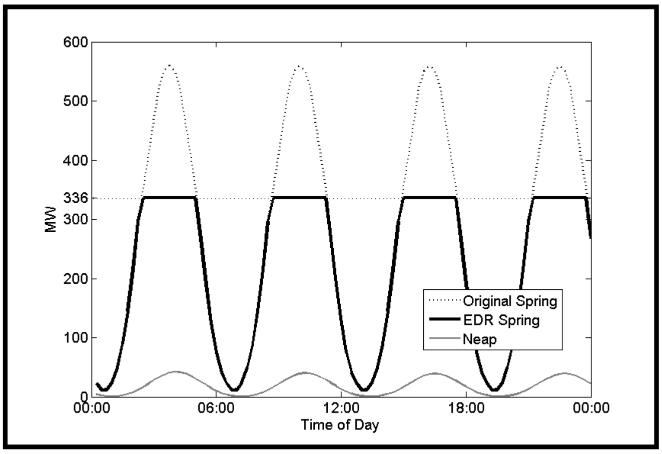


**Fig. 4.11.** Tidal power over the spring-neap cycle [X]

In fact, in some instances, EDR is imposed to such an extent that the turbine reaches its maximum output even during neap tide. An example of this is Strangford Lough. In this site, the neap tidal velocity is approximately 50% of spring tidal velocity

[2]. Thus, EDR of 50% ensures that the output can reach its peak even during neap tides; consequently, the turbine presents a very high load factor. EDR spills excess energy during the hours of spring tides thereby increasing the overall average power output of the turbine.

### 4.2.1. Types of turbines

As previously commented, tidal current turbines extract the kinetic energy from the currents to generate electricity. Currently, there are mainly two types of turbines, horizontal axis and vertical axis tidal current turbines.

- **Horizontal axis tidal current turbines**:

The turbine blades rotate about a horizontal axis which is parallel to the direction of the water flow. They are arrayed underwater in rows, similar to some wind farms. The optimum operating point of the turbines is for coastal currents speeds between 4 and 5.5 mph [6]. In those currents, a 15 meter diameter tidal turbine can generate as much energy as a 60 meter diameter wind turbine. The ideal locations for tidal turbine farms are close to shore in water depths of about 20–30 m.

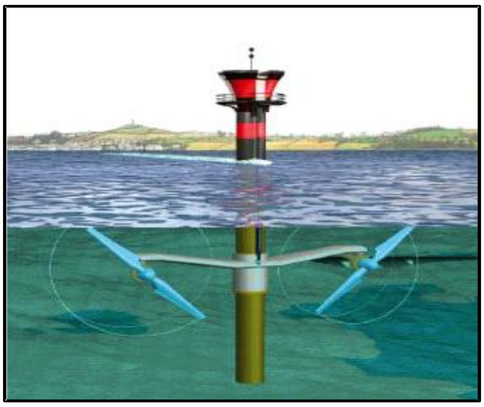

**Fig. 4.12.** Horizontal axis turbines [XI]

Horizontal turbines have slightly higher efficiency than vertical turbines. However, as they depend on the current direction, a mechanism to make the blades rotate is needed, generally, they are very complex.

Following, some real examples of this type of turbines are mentioned.

- **<u>Seaflow turbine</u>** [28]

**Fig. 4.13.** Seaflow turbine [XII]

It has an 11 m diameter rotor, with full span pitch control. It is mounted on a steel tubular pile, 2.1m in diameter, set in a hole drilled in the seabed and tall enough to always project above the surface of the sea. It is installed in a mean depth of 25 m, 1.1 km off the nearest landfall in North Devon, UK. Under favorable conditions it has exceeded its 300 KW rated power with a 15 rpm rotor. It is not grid-connected, dumps its power into resistance heaters. This device was developed by the Marine Current Turbines (MCT)

- **<u>The E-Tide project</u>** [29]

**Fig. 4.14.** E-Tide project [XII]

It was developed by Hammerfest Strom. This turbine can be installed on the seabed offshore or near shore depending on the tidal current strength. The blades of 15-16 m are able to rotate on their own axes, allowing the turbine to be optimized to current conditions and also operate in both directions of the tide. A 300 KW system was tested, currently, a larger design is being developed that will provide 750-1000 KW of power.

- **Vertical axis tidal current turbines**

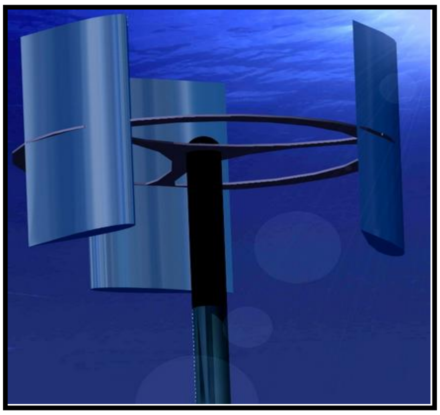

**Fig. 4.15.** Vertical axis turbine [XIV]

Vertical axis turbines are cross-flow turbines, with the axis positioned perpendicular to the direction of the water flow [30]. Cross flow turbines allow the use of a vertically oriented rotor which can transmit the torque directly to the water surface without the need of complex transmissions systems or an underwater nacelle. The vertical axis design permits the harnessing of tidal flow from any direction, facilitating the extraction of energy not only in two directions, the incoming and the outgoing tide, but making use of a full tidal ellipse of the flow. Moreover, the blades are easily built and their span can be easily increased [27]. However, this type of turbines experiment a lot of vibrations, as the forces exerted on the bladders are very different, consequently, it is difficult to reach stability. In vertical axis turbines as in horizontal axis ones the rotation speed is very low, around 15 rmp.

Below two vertical axis projects are introduced.

- **Kobold turbine** [31]

**Fig. 4.16.** Kobold turbine [XV]

This turbine main feature is the high starting torque that makes it able to start spontaneously even in loaded conditions. A pilot plant is moored in Messina, Italy, in an average tidal current of about 2 m/s. With a current speed of 1.8m/s, the system can produce a power of 20 KW.

- **Blue energy project** [32]

Four fixed hydrofoils are connected to a rotor that drives an integrated gearbox and an electrical generator assembly. The turbine is mounted in a concrete caisson which anchors the unit to the ocean floor. The generator and the gearbox are placed above water surface and are readily accessible for maintenance and repair. A unit turbine output power is expected to be about 200 KW, for large scale production, multiple turbines are linked in series.

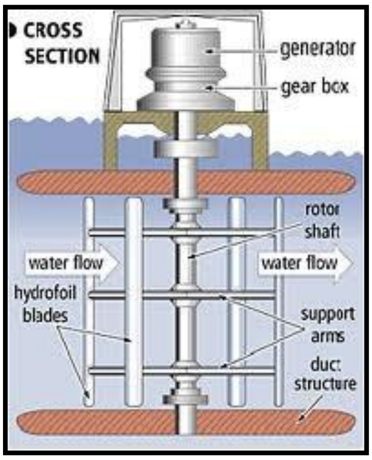


**Fig. 4.17.** Blue energy Project [XVI]

# 5. Current Issues

## 5.1. Tidal Barrage

Tidal range is considered a mature technology, is reliable and has excellent potential. However the current issues restricting its development are the high construction costs and the environmental impact. The economic aspects will be tackled in depth on the following chapter; however, on the following paragraph some comments are made concerning high constructions costs as well as the environmental impact of such technology.

The construction of a tidal barrage requires a vast quantity of materials to withstand huge loads produced from the dammed water. The resulting high construction costs are considered one of the greatest issues when deciding whether or not a site is economically viable for tidal energy extraction.

Another great issue concerning tidal barrages is the environmental impact. Considering the benefits of this technology, it can be said that tidal power is a nonpolluting technology and generally displaces coal and hydrocarbon fuels. For example, a tidal barrage would save up to 1,000,000 tons of carbon dioxide emissions per TWh [7]. It is also a benefit the fact that provides protection against coastal flooding within the basin during very high tides by acting as a storm surge barrier. However, on the other hand also presents some environmental impacts given that building a dam across an estuary may change the flow of the tidal current affecting to marine life. Besides that, water quality within a basin may also be affected in aspects such as sediment transportation; however, not all changes in sediment transportation are negative given that marine life may flourish at sites where they are not normally found [4]. The impact on marine life and maritime traffic may also be determinant. Regarding marine life, it has potential effect on fish, particularly in migratory species, as may arise mortality at the turbines. Such impacts can be reduced by using fish passes and diversion, though further research is needed. Concerning, maritime traffic problem, it has to be said that is easier solved for an ebb generating system where the basin is kept at much higher water level than in flood generation system.

Finally, non-energy benefits must also be considered when assessing viability of tidal barrage projects. Some of these benefits such as land reclamation and improved aquaculture are shown in China [7].

## 5.2. Tidal current

Tidal current technology stills in its infancy [33]. However, recent developments open up prospects for commercial deployment of some schemes in the near future. Up to the moment, some down-scale models and full-scale prototypes have been developed, while some are currently in operation others are about to be installed, mainly in Europe. Furthermore, as previously mentioned, since May 2005, the first dedicated test centre, the European Marine Energy Center, EMEC, has been operational in Orkney, Scotland.

Although nowadays this technology costs are very high, it is anticipated that they will decrease as the technology advance, as it is detailed in the following chapter. The current issues restricting the developments of tidal current turbines are installation challenges, maintenance, electricity transmission, loading conditions and environmental impacts.

Tidal current devices have to support huge thrusts due to the density of the water [34]. Resisting these loads will suppose the use of greater amounts of materials or strong materials, which will result an increase on the capital costs.

Concerning maintenance, easy access to the turbines is required; the use of a ship for routine maintenance and repair or tidal current devices will make this task hazardous, difficult and expensive, therefore, it is necessary that at the design stage, a set of measures are set to reduce the frequency and the difficulty of maintenance.

Electricity transmission is another concerning issue. Generators should be developed to operate at higher voltages, preventing the need to install transformers at, or below, the surface. Generally, tidal current energy resource is often in area where grid access is limited; upgrading the grid network may be required, this might be costly and public discontent.

As for environmental impacts of tidal current devices are believed to be minimal in comparison with tidal barrages. The areas at which tidal turbines will be located are areas where marine species are not commonly found.

# 6. Economic assessment

Investments in renewable energies, such us wind, solar and photovoltaic, to reduce greenhouse gas emissions and to contribute to a sustainable development are now a reality. However, fossil fuels remain as the main source of energy and our dependence on them still more than considerable.

Tidal power presents a great potential to become an important part of the electrical structure. Tidal range is considered a mature technology as it is in the commercial stage, while tidal current still in its infancy. However, there are some uncertainties about the costs and benefits this energy can provide.

This section is intended to make an assessment of the costs involved in developing tidal energy technologies as well as making an estimation of them. Finally a comparison between the results will be carried out and the potential of both technologies will be estimated.

## 6.1. Methodology

The analysis is based on data extracted from different studies carried out in UK, given that due to its potential, between 15% and 20% of current UK electricity demand could be met by ocean energy [35].

A Base Case scenario has been considered for the study. On *Table 6.1.* Base case assumptions are displayed.

| Base case assumptions | Values |
|---|---|
| Project life | Tidal stream : 20 years<br>Tidal range: 40 years financial life, 120 years design life |
| Construction periods | Tidal stream deep: 2 years<br>Tidal stream shallow: 3 years<br>Tidal range: 5 years |

| | |
|---|---|
| Load factor | Tidal stream deep- 37%; Tidal stream shallow- 35%; Tidal range- 20% |

**Table 6.1.** Base Case Assumptions [XVII]

The load factor, ratio between the output generated by the device and the maximum output it could produce, used for the study were developed directly from the load factors provided by the technology developers. Although the analysis is based on a range of technologies the numbers presented are averaged, therefore they are not representative for any given technology in a particular site [35].

Moreover, in order to consider different scenarios, three sites conditions have been considered in the available resource sites providing a high, medium and low resource site.

| Description | High resource | Medium resource | Low resource |
|---|---|---|---|
| Tidal stream deep | 3.8 m/s | 3.2 m/s | 2.8 m/s |
| Tidal stream shallow | 3.6 m/s | 3 m/s | 2.4 m/s |
| Tidal range | N/A | 700 MW | 150 MW |

**Table 6.2.** Resource conditions [XVII]

Furthermore, key factors affecting energy cost have been identified. Principally they are constituted by capital costs (Capex) and operating expenditures (Opex). These costs include:

- CAPEX:
  - Construction cost
  - Electrical systems infrastructure costs
  - Pre-development costs

- OPEX
  - Operating and maintenance costs (O&M)
  - Insurance costs
  - De-commissioning costs
  - Other costs

Finally, taking into account all the cost assumptions considered, the levelised costs of the electricity (LCOE) for both technologies have been calculated and compared. The levelised cost is the price at which electricity must be generated to break even. The LCOE is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operation and maintenance, cost of fuel, cost of capital. However, it is a complex indicator to determine because it depends on many factors. Some of them greatly depend on the location of the farm such as capacity factor and O&M costs, while the discount rate is dependent on the investor's decision. The following equation displays how the LCOE has been calculated.

$$\mathbf{LCOE} = \frac{\sum_{t=1}^{n} \frac{\mathbf{I_t + M_t + F_t}}{(\mathbf{1+r})^{\mathbf{t}}}}{\sum_{t=1}^{n} \frac{\mathbf{E_t}}{(\mathbf{1+r})^{\mathbf{t}}}} \qquad \text{Eq. 6.1}$$

Where:

- $I_t$ = Investment expenditures in the year t
- $M_t$ = Operations and maintenance expenditures in the year t
- $F_t$ = Fuel expenditures in the year t
- $E_t$ = Electricity generation in the year t
- $r$ = Discount rate
- $n$ = Life of the system

As previously mentioned, tidal range is a commercial technology while tidal current stills in its infancy, for this reason, the way to tackle the analysis is slightly different concerning future costs. Following that, each case is specified.

## 6.2. Tidal current economics

Tidal stream industry began to develop during the 1990s, for this reason it is assumed that the technology stills in its infancy as devices are at early stages compared to other renewable and conventional plants, and crucially, optimal designs have yet to be converged upon. Consequently, is subjected to high initial costs and high learning. To make a more concrete analysis and to estimate the progress of the costs three different stages in the technology development have been defined:

1. **- Pre-demonstration**. Prototypes costs
2. – **Demonstration.** First 10 MW farm, large scale demonstration project costs
3. – **Commercial**. A 10 MW farm after technology developer has installed 50 MW. Technology fully commercialized.

Tidal stream resource has been split into shallow (under 40 m depth) and deep (over 40 m depth) due to the different deployment method required. However, the shallow and deep technologies are potentially the same apart from the structure and the foundations or mooring. Therefore, there will be a benefit on learning from each other. On *Table 6.3.* the technologies main characteristics are shown.

| | **Tidal strem shallow** | **Tidal stream deep** |
|---|---|---|
| First 10 MW farm operational | 2015 (20 MW) | 2018 (15 MW) |
| 10 MW commercial farm operational after 50 MW | 2017 (100 MW) | 2020 (60 MW) |
| Water depth | < 50 m | > 50 m |
| Mean power | 3 m/s | 3.2 m/s |
| Mean base case capacity factor | 35% | 37% |
| Mean project life | 20 years | 20 years |
| Mean construction period | 3 years | 2 years |

**Table 6.3**. Tidal stream shallow and deep characteristics [XVII]

As set out below, in the medium term tidal current shallow is expected to be more developed, as greater deployment is estimated. Under Base Case assumptions 200 MW tidal stream shallow is expected to be deployed globally versus only 23 MW for tidal stream deep by 2019. However, in the long term tidal stream deep deployment is expected to exceed tidal stream shallow, in both globally and the UK due to the higher resource available.

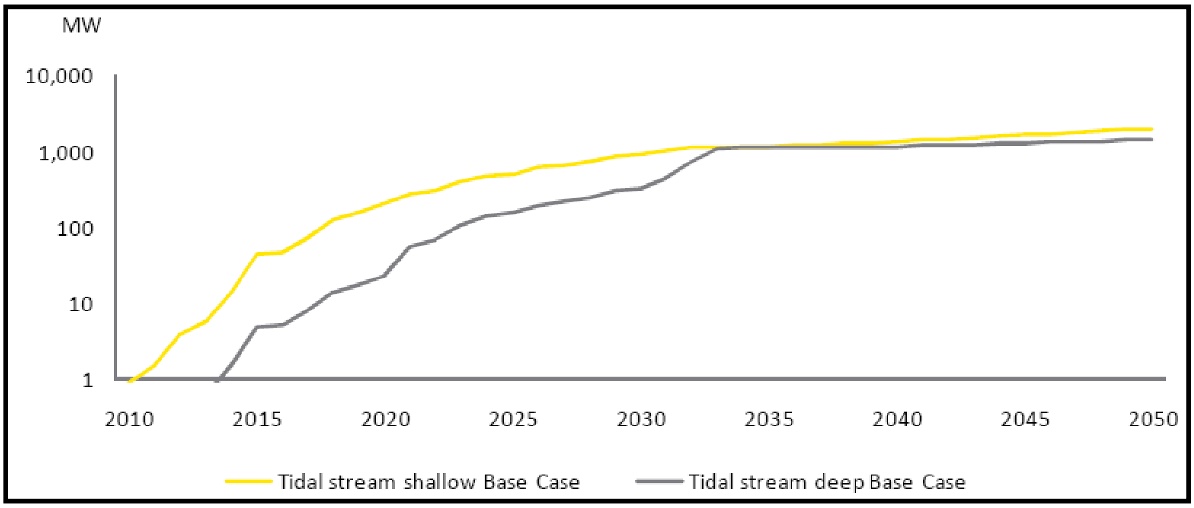


**Fig. 6.1.** Tidal stream shallow and deep deployment in UK [XVII]

### 6.2.1. <u>Currents costs</u>

Costs depend strongly on the amount of machines built and installed. With no commercial tidal stream projects, costs come from large-scale prototypes. However, the capital costs of these are likely to be greater than production models for commercial projects because prototypes are built one to one whereas commercial models are built in batches and also because design improvements will derive from prototype testing and may reduce cost and/ or increase performance [25].

For tidal current farms capital costs and operating and maintenance costs have been envisaged as *Fig 6.2.* shows. Should be mentioned that O&M costs at present are more difficult to estimate than capital due to the lack of experience, although it is possible to infer costs from experience in other farms such us offshore wind farms.

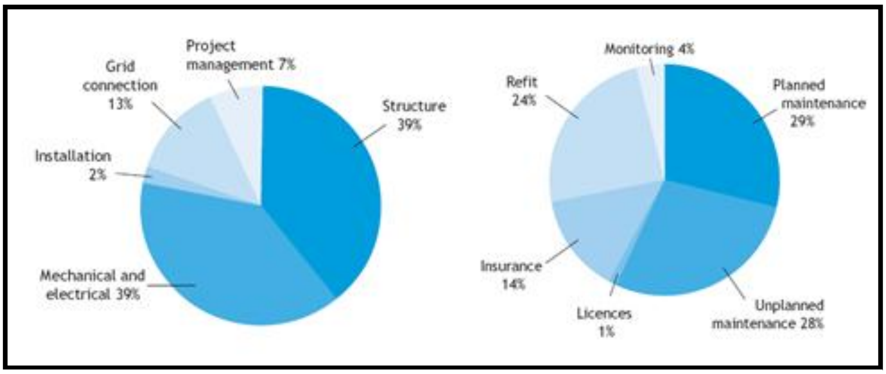


**Fig. 6.2.** Breakdown of capital costs and O&M costs from tidal stream farm [XVIII]

From all the data collected, some values and graphs have been extracted. Carbon Trust (CT) published that first prototype tidal stream energy generators could cost up to £8000/KW, however some devices were built for under £4800/KW. For first production models, it estimates that the costs range from £1400/KW and £3000/KW. On the other hand, Black&Veatch (B&V) provides the following figures, where the capital expenditure and operating costs are displayed; the error bars display the costs uncertainty. It is shown that for shallow tidal stream, first prototype costs range from £7,500- £12,400 /KW while for deep tidal stream the costs are estimated to be around £7,300- £9,900 /KW, considering these values, it can be conclude that the average Capex cost envisaged for both sources is very similar, as the mean value provided by B&V considering both cases is around £9000/KW. Regarding first production models, namely, commercial projects, the mean value for tidal stream shallow is around £3.200/KW and for tidal stream deep is around £3.300/KW. In this case, the values provided by B&V are slightly higher than the ones given by Carbon Trust. A possible reason for this difference is the time when these data was published, as CT values date from 2006 while B&V information was published in 2010. The more recent and specific is the data the more accurate it will be, subsequently, it has been considered that B&V values are more precise as more research and prototypes have been developed during the last four years. Moreover, CT distinguishes between tidal stream shallow and deep so more accurate values for each case are given.

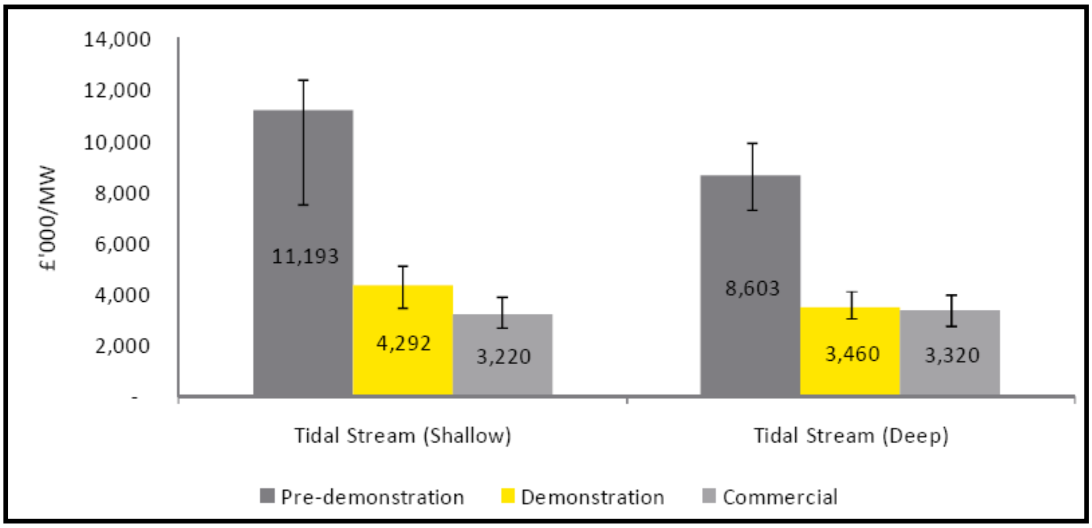


**Fig. 6.3.** Tidal stream shallow and deep Capex [XVII]

An important fact to point out from *Fig. 6.3* is the difference between tidal stream shallow and deep costs. It is observed that for pre-demonstration stage, costs for tidal stream deep are less than for tidal stream shallow, this fact is because tidal stream shallow is considered to develop earlier than tidal stream deep. Therefore tidal stream deep is assumed to learn from tidal stream shallow resulting in lower costs.

On the following figure the Opex costs are displayed, it is shown a decrease on these costs as the technology develops. This fact was predictable because as the technology develops, improvements in both, design and performance are introduced and consequently costs related with operation and maintenance decrease.

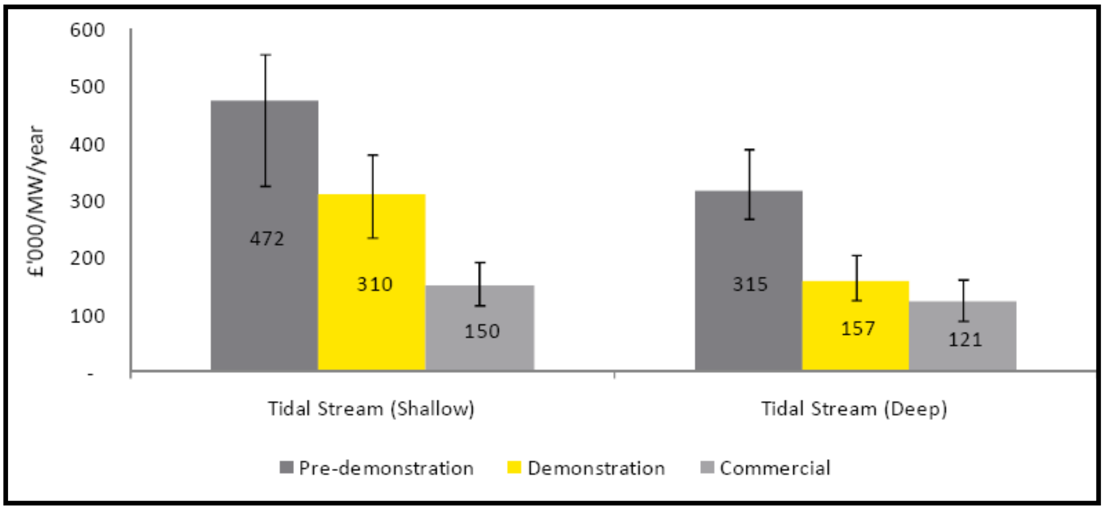


**Fig. 6.4**. Tidal stream shallow and deep Opex [XVII]

The capital and O&M costs of early tidal stream energy generators are expected to be higher than long-term costs due to several practical and economic factors. Firstly, the materials used nowadays to build the devices are not the most suitable as it is a very new technology; therefore, bespoke solutions to reduce costs are the subject of R&D and will take time to develop. Moreover, there is a limited experience in installing, operating and maintaining the devices; consequently the risks are reflected on the higher costs. Last but not least, only a small volume of devices are produced and installed, which means novel manufacturing processes and the use of customized vessels for installations, operation and maintenance which suppose and increase on the costs [25]. Bearing all the mentioned aspects in mind, it can be conclude that current costs for tidal stream energy are much higher than conventional and other renewable energy generation due to the early stage of the technology.

### 6.2.2. Future costs

After evaluating tidal stream current costs and important issue to tackle are its future costs. For this reason the following question is arise, can costs of tidal stream electricity be reduced to become cost-competitive with conventional and other renewable generation? To approach this issue, firstly some ways to reduce costs have been identify and then the future costs have been predicted.

There are four possible ways of reducing cost of energy:

1. Concept design development. Any development in concept design brings an increase in performance as well as costs reduction.
2. Detailed design optimizations. Design improvements are linked with cost reductions and/ or performance increase.
3. Economies of scale, cost reduction as production increases.
4. Learning in production, construction, installation and O&M. The more learning is achieved the better the processes become, and thus, the optimal process is closer.

All this cost reductions are not independent from each other, for this reason it is impossible to identify the benefits of each mechanism separately. However, it is believed that design improvements are likely to be significant in the short to medium term.

There are two key factors that are very sensitive when concerning tidal stream future costs, the discount rate and the financing period [25]. It is expected that as the installed capacity increases and risks decrease the return rate required financing tidal current projects decreases. In fact, in several studies from B&V a return rate of 15% has been considered for initial projects while for long term projects an 8% rate has been applied. On the other hand, the financing period mainly depends on the funding source and the investors' risk/ reward expectations.

To predict future costs learning curves have been used. The learning curves assumed on the study have been derived after considering empirical learning rates from other emerging renewable energy industries [35]. The closest analogy for tidal stream industry has been assumed to be the wind industry, however, in wind industry the technical solution is consolidated whereas in tidal stream industry although it seems that technology is converging on horizontal axis turbine, there are a number of alternative concepts still being developed. Furthermore, it is also know that most of the learning occurred in wind power was at small scale with small units, whereas tidal stream, on the other hand, requires large investments to deploy prototypes, and therefore requires a smaller number of more risky steps to develop. This tends to suggest that learning will be slower.

Learning rates are assumed to be constant in deployment through time, but in reality they are likely to be bumpy, and may slow down or fall to zero as the technology reaches market maturity. On the following table the average learning rates for base case, pessimistic and optimistic scenarios are shown, they have been developed bearing the above observations in mind.

| | Base Case | Pessimistic | Optimistic |
|---|---|---|---|
| Tidal stream shallow | 13.0% | 9.0% | 16.9% |
| Tidal stream deep | 12.5% | 9.6% | 16.4% |

**Table 6.4.** Average learning rates for tidal stream shallow and deep [XVII]

### 6.2.3. Levelised costs

Today levelised costs for both, tidal stream deep and shallow are high, but it is assumed that they will decrease in the long-term due to several reasons:

- Learning rate. An average learning rate of 13.0% for tidal stream shallow and 12.5% for tidal stream deep first commercial deployments is considered.
- Declining rate of increase in underlying costs
- Risks reduction
- Design improvements and technology development.

On the following figures the levelised costs for both, tidal stream deep and shallow, are shown. As it is displayed below and it was previously mentioned tidal stream shallow levelised costs are lower in the short-term, for this reason it is assumed that this technology will be deployed before tidal stream deep. However in the long-term due to both, greater deployment potential of tidal stream deep and learning from shallow technology, levelised costs of deep technology will decrease and they will be lower than tidal stream shallow's. It is also displayed on the below figures how the discount rate decreases with time, in other words, as the install capacity increases.

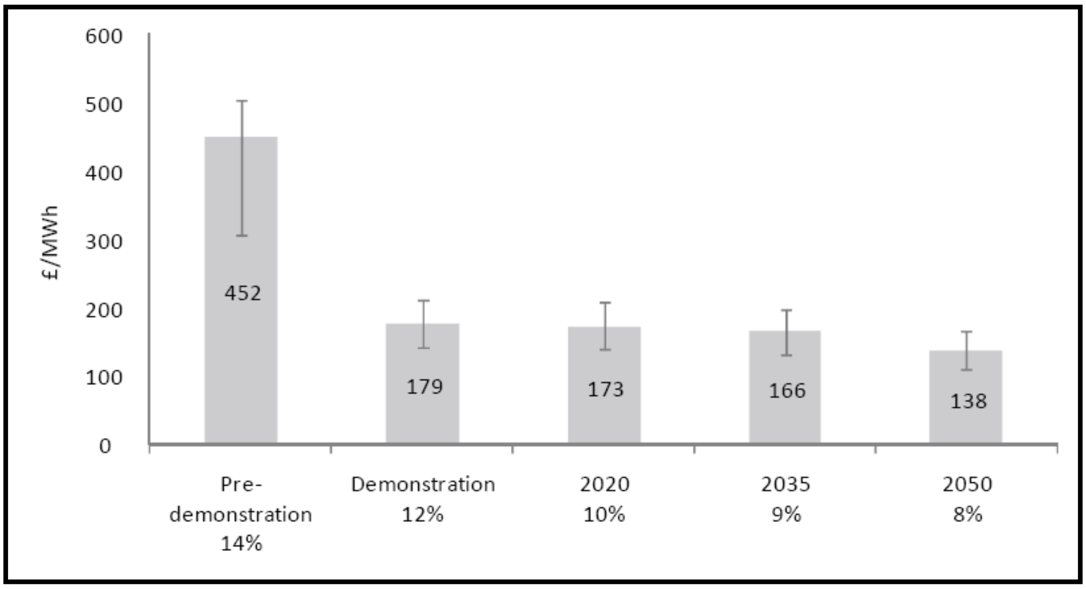


**Fig. 6.5.** Tidal stream shallow levelised costs [XVII]

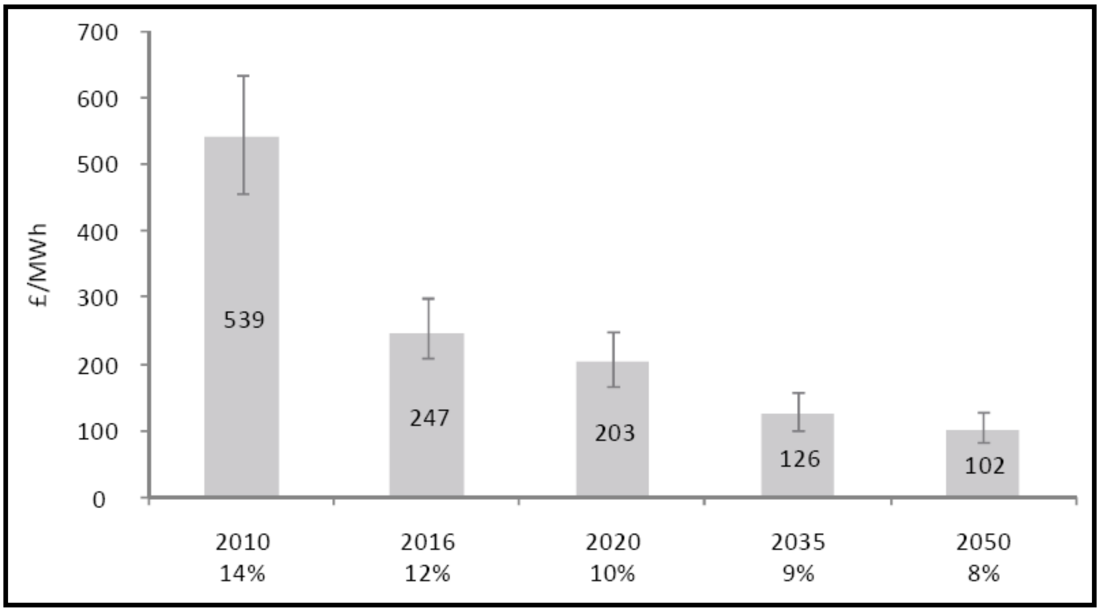


**Fig. 6.6.** Tidal stream deep levelised costs [XVII]

## 6.3. Tidal Range economics

Tidal range projects are considered to be large projects, which require mature engineering practices and have long project lives, longer than tidal stream. Tidal barrage is considered a commercial technology; however significant deployment does not occur because of long lead times [35]. On the following table, tidal range main characteristics are shown.

| | TIDAL RANGE |
|---|---|
| Commercial stage | Already commercial today |
| Distance from shore | 0 Km |
| Typical project capacity | 100-700 MW |
| Average commercial capacity factor | 20% |
| Typical project life | 40 years financial life; 120 years design life |
| Typical construction period | 3-6 years |

**Table 6.5.** Tidal range characteristics [XVII]

UK has a significant tidal range resource, with the second highest tidal range site being located in the Severn Estuary with 177TWh/year; other resource sites include Mersey (1.4 TWh/year), Duddon (0.212TWh/year), Wyre (0.1331 TWh/year) and Conwy (0.06 TWh/year). All in all, through tidal range potential there is an opportunity to provide up to 13% of UK's electricity from tidal range alone. On *Fig. 6.7.* the deployment curves related to tidal range in UK are shown. These curves are based on varying the sizes and numbers of projects going ahead. For the base case assumptions it assumed that 150MW Solway project reaches financial close by 2018, 700MW Mersey project in 2020 and 100 MW Duddon in 2022. The high case incorporates the Wyre and the low case is formed of Solway and Duddon.

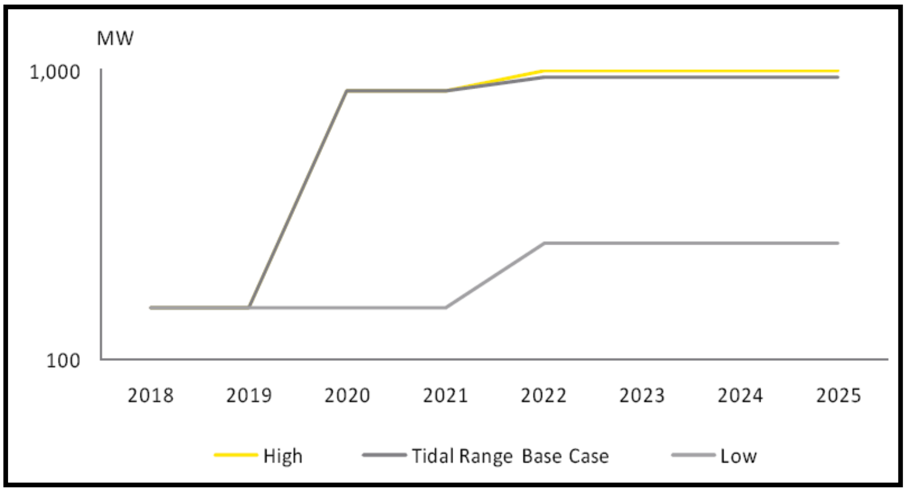


**Fig. 6.7.** Tidal range deployment in UK [XVII]

As tidal range is a commercial technology, no pre-commercial or demonstration stages have been studied. For this reason, no learning rate associated has been considered. Concerning the technology costs there is not an exact value as several factors such as the location of the dam, the discount rate considered, the information source and the date of such information between other factors, have significant impact on it. For instance, in Black and Veatch study focused on UK ocean energy (2006) a Capex of £ 2,700,000/MW and Opex £34000/MW per year is considered, while the Organization for economic co-operation and development published in "Projected costs of Generating Electricity" (2010) that the Capex for tidal barrage in Australia was 3207 USD/KW, considering a discount rate of 10%. Converting these amount to £/MW, we find a CAPEX of 1,940,523 £/MW. Moreover, Atkins Consultants Ltd. carried out an study called " Tidal Electric Limited Feasibility Study for a Tidal Lagoon in Swansea Bay" (2004) where the estimation of capital and operating costs for tidal lagoon in Swansea Bay where displayed. In the article it was commented that the costs were only indicative given that there was no competitive tender against a specific design. Following a breakdown of capital costs is shown.

| **COST** | **AMOUNT (£m)** |
|---|---|
| Impoundment | 48,5 |
| Turbine Hall structure | 12,7 |
| Turbine Plant and equipment | 14,1 |
| Maintenance equipment | 0,1 |
| Electrical connections | 3,0 |
| Access Jetty | 0,5 |
| Navigation lights | 0,1 |
| **TOTAL** | **79** |

**Table 6.6.** Tidal barrage breakdown costs [XVII]

Considering and installed capacity of 60 MW, the initial cost estimates that the capital costs are of the order of 1,300,000 £/MW.

Moreover, some remarks about some components costs concerning a tidal barrage should be done. It is interesting to compare the costs associated to the concrete used for the power houses; due to the lack of recent information, some data published some years ago has been used. The costs have been updated to present time, by 2% every year, average inflation over the last 20 years. From the table below we can see the economies of scale effect, the cost decrease as the quantity of concrete needed increases, reinforce concrete for the smaller scheme with fewer caissons (Conwy) is more expensive than for the larger scheme (Severn) [36].

| **Scheme** | **Base date** | **All- concrete cost (£/m$^3$)** | **Approx. updated cost (£/m$^3$)** |
|---|---|---|---|
| Conwy | 1990 | 586 | 888 |
| Duddon | 1993 | 576 | 823 |
| Severn | 1988 | 440 | 680 |

**Table 6.7.** Costs of reinforced concrete [XIX]

Another cost to explore is the cost of turbines and generators. The following table summarizes the costs of turbines adopted for other tidal schemes.

| **Item** | **Conwy** | **Duddon** | **Wyre** |
|---|---|---|---|
| Turbines + generators costs (£M) | 15.53 | 49.52 | 22.50 |
| Installed capacity (MW) | 33 | 100 | 54.4 |
| No. x diameter of turbines | 6 x 4.0 m | 10x 5.5 m | 4 x 6.2 m |
| Cost/KW installed (£) | 471 | 495 | 414 |
| Base Date | 1990 | 1993 | 1991 |
| Updated cost (£/KW) | 714 | 707 | 615 |

**Table 6.8.** Turbines and generators costs [XIX]

From the information displayed, it is conclude that the cost per KW installed decreases as the turbines size increases, which is to be expected, because otherwise, to achieve the output of one big turbine you may need two small turbines, consequently the costs increase.

The high capital costs and the long construction times, make tidal energy quite sensitive to the discount rate for the capital employed. Several studies carried out on the Severn Barrage have shown and almost linear relation between the discount rate and the cost of electricity generation [7].

As previously mentioned, tidal barrage construction costs are considered one of the greatest issues when deciding whether or not a site is economically viable for tidal energy extraction [4]. However, some construction techniques have been developed. A recent development is the diaphragm wall method construction which will save up to 40% on construction costs of barrages. Another option is to use steel, either partially or wholly in caissons manufacture, giving place to a lighter structure, although, significant savings will not be achieved as corrosion protection methods still have to be solved [7].

Power transmission to remote locations it has not been tackled yet. A great development that would have a considerable influence on the viability of many proposed tidal energy developments in remote areas is the high-voltage-direct-current (HVDC) transmission. Its main feature is that allows transmission distances of up to 10,000 km with losses of 3% per 1,000 km, and AD / DC / AD conversion with losses of only 1% due to the silicone induction thyristors.

Furthermore, when considering economic viability of tidal power schemes, two main factors have to be considered: the treatment of environmental cost and financial climate. The treatment of environmental costs determines the extent to which tidal energy, green energy, must compete with conventional energy sources, priced on the basis of international costs that may only include partially the cost to the environment due to their emissions. The financial climate determines capital intensives projects sensitivity to interest rates and risks. Tidal power projects are capital intensive and require long construction periods, for these reason, they are very sensitive to the financial method and to the discount rate [7].

### 6.3.1. Levelised costs

After recollecting some data concerning tidal range electricity production and costs and bearing in mind all the points above mentioned, the levelised costs have been determined. On the figure below, provided by Black&Veatch, tidal range levelised costs are shown; as it is displayed, it is estimated that by 2020 the LCOE is around £279/MWh while for 2050 is expected to be around £229/MWh, not a considerable decrease is seen due to technology maturity. At the same time, the Organization for economic co-operation and development published and LCOE of 210,796 £/MWh, it is a little bit lower, however, it seems to be reasonable as the capital costs they estimate are lower too.

Another aspect to point out is that the discount rate only decreases slightly, as the risk associated with tidal range projects does not fall very much due to its maturity.

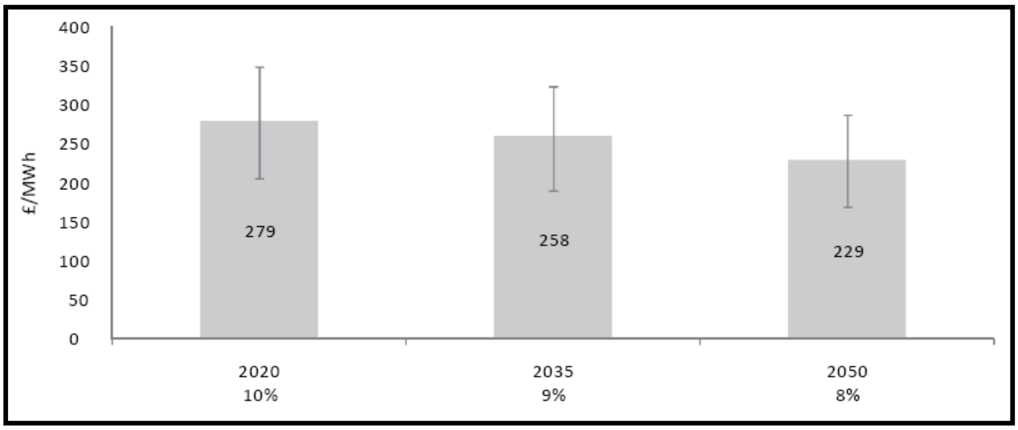


**Fig. 6.8.** Tidal range levelised cost [XVII]

## 6.4. Conclusions

The following table displays a summary of the levelised costs.

| Technology | Cost scenario | 2020 | 2035 | 2050 |
|---|---|---|---|---|
| Tidal stream deep | High | 250 | 159 | 129 |
| | Medium | 203 | 126 | 102 |
| | Low | 166 | 102 | 82 |
| Tidal stream shallow | High | 211 | 199 | 166 |
| | Medium | 173 | 166 | 138 |
| | Low | 141 | 134 | 111 |
| Tidal range | High | 349 | 323 | 286 |
| | Medium | 279 | 258 | 229 |
| | Low | 205 | 190 | 168 |

**Table 6.9.** Summary of levelised costs (£/MWh)

After considering all data above exposed, several conclusions have been reached. Regarding tidal current, costs are relatively high given the early stage of the industry; however, there is a clear potential to become competitive with other generation forms in the future as the costs will considerably decrease as the installed capacity increases. Another fact that contributes to cost reduction is technology development, meaning, and improvement in the three, materials, design and production. To ensure technology development academic and industrial R&D, engineering design and prototype testing is needed. Therefore, it is important that both, government investment and private equity support the technology to guarantee the feasibility and survivability of tidal stream industry. Academic R&D is likely to come mainly from governments, although this may be supplemented by private equity via technology development, companies and/or universities. A combination of R&D grants, venture capital and strategic investments is probable to support technology development companies in engineering design and prototype testing.

Furthermore, to achieve a quick technology development, and therefore a quick reduction of costs, the number of technology developers and the relation between them is a crucial issue. It is essential that there is cooperation between them in order to ensure a safe and agile development. The success on technology development is also likely to depend on the approach to managing the risks. On the one hand, there is a commercial pressure to develop rapidly in order to maximize the value of technology development investment, which considers that a delay in development is a delay in learning. However, a counter argument is that a slower, more progressive approach is better to manage risks. All in all, I believe that a combination of both, importing knowledge from other industry sectors and carrying out some prototypes testing will lead to the fastest development and lowest risk.

On the other hand, regarding tidal range, although there is a wide range of capital costs due to the different factors affecting them, it seems that they are considerably high due to a heavy capital nature of the technology and lack of learning potential, as well as, limited sites for deployment. However, its deployment can bring several benefits; not only produces energy without greenhouse emission but it also means improvement of the road connection between sides. Furthermore, tidal barrages turn to be a tourist attraction and part of the industrial inheritance.

Focusing on the LCOE, it is seemed that although tidal barrage is a mature technology the price predicted for each MWh on 2020 is higher than for tidal stream, on average around a

33%, and what is more, as there is not much scope for costs reduction on tidal range technology, on 2050 tidal range costs per MWh are predicted to be around 48% higher than tidal stream. Analyzing these values, it can be concluded that the potential of cost reductions for tidal stream is high due to technology development and learning, whereas tidal range regards very high deployments costs and does not have much scope to reduce them as it is already considered a commercial technology.

# 7. Technological assessment

As previously mentioned, a tidal barrage can operate in three different modes, ebb generation, flood generation and bi-direction generation. While for the first two, one-direction turbines are used for the third operation mode, reversible turbines are employed. This chapter aims to present a report regarding both technologies, as nowadays there is an open debate of which technology is more efficient. So far, both types of tidal barrage have been built, for instance, La Rance and Jangxia tidal plants use bidirectional turbines while Annapolis tidal barrage uses one direction turbines.

The purpose of this assessment is to identify which technology, one direction or two-direction turbines, can generate more electricity under the same operating conditions. For this, their characteristic curves have been used and their characteristic parameters have been calculated. The study is based on the calculation method defined on “JIANG XIA CHAO XI SHI YOU DIAN ZHAN” book, attached in the Annex, and from which a clear and precise methodology has been designed to calculate the power limitation curve and the water head.

Aiming to approach these technologies, firstly a brief explanation of both technologies is included. Following that, the methodology used is exposed as well as the results obtained when applying it. Subsequently, both technologies are discussed and compared. Finally a cost analysis is carried out.

## 7.1. Turbines

As it was previously mentioned in chapter *4.1.1*, currently three turbines technologies are used in dams, bulb, rim and tubular turbines. The first ones, bulb turbines, are reversible, they can operate in bidirectional mode, namely, they can generate during both, ebb and flood tide. Moreover, they can also act as a motor to pump water to the basin. The other two technologies can only generate power in one direction.

## 7.2. Methodology

The calculation method aims to calculate the electric energy produced by a tidal barrage; for this, some data such as the relevant tidal features, the reservoir storage capacity curve and the turbines characteristic curves have been used.

The approach of this method is based on a trial procedure. For this, the reservoir storage capacity variation, $\Delta V$, during a period of time $\Delta T$ is compared with the flow, Q, flowing through it during the same period of time; $Q \cdot \Delta T <=> \Delta V$. From this comparison the water head, H, is determinate, which is the level difference between the sea and the reservoir. Finally, by knowing these parameters and by using the turbine characteristic curve, the power and the electric energy produced can be determinate.

The detailed process to calculate the electric energy production for forward turbining is attached on the Annex.

### 7.2.1. Method 1: Power limitation curve calculation

The aim of the following method is to calculate the power limitation curve (X[i] - q[i]). The points constituting the curve are the ones that provide the maximum power output. The procedure followed to establish the curve, was to calculate for each value of n11, the output obtained by m points; in our case of study, up to 6 points were explored, however, if more precision was required, more points could be explored. Subsequently, for each n11 only the maximum power output was plot on the graph. Below the procedure followed is shown.

The parameters involved on this method are:

- $H_{min}$: Minimum water head
- $H_{max}$: Maximum water head
- $H_r$: Design water head
- $n_r$: Rated speed
- n11[i]: Unit speed
- Q11[i,m]: Volume flow rate
- P11: Unit output
- $\eta_t$: Turbine efficiency

- g : Generated energy
- S: Quantity of generating units

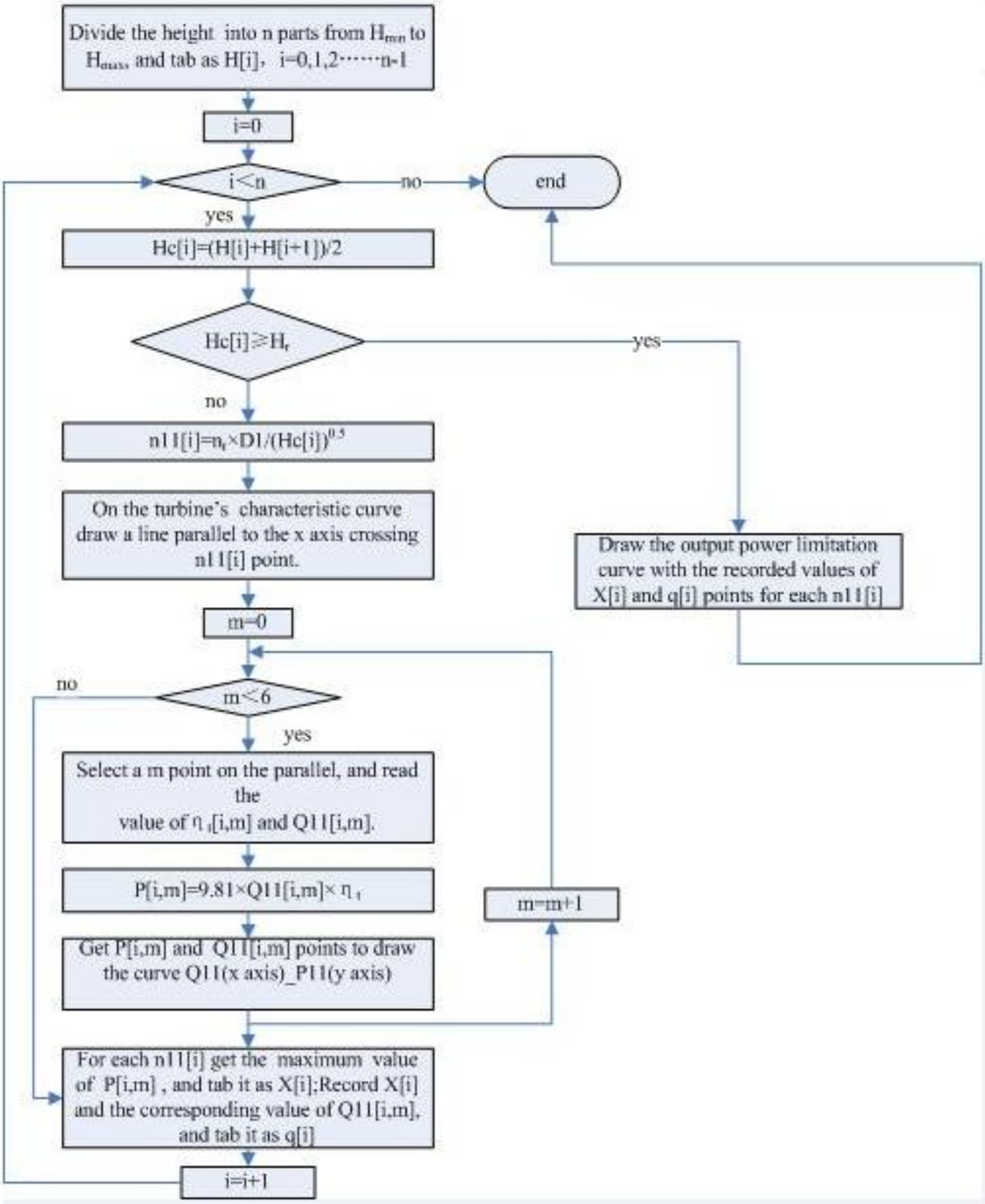


**Fig. 7.1.** Power Limitation Curve Calculation [XX]

### 7.2.2. Method 2: Head calculation

The following method has been designed from the calculation method previously presented. The aim of it is to determine the water head, and consequently the electric production. Bellow, are displayed the steps followed.

Concerning this procedure, it has to be said that while n11 values are calculate through formula, Q11 values have been extracted from the power limitation curve obtained after applying method 1.

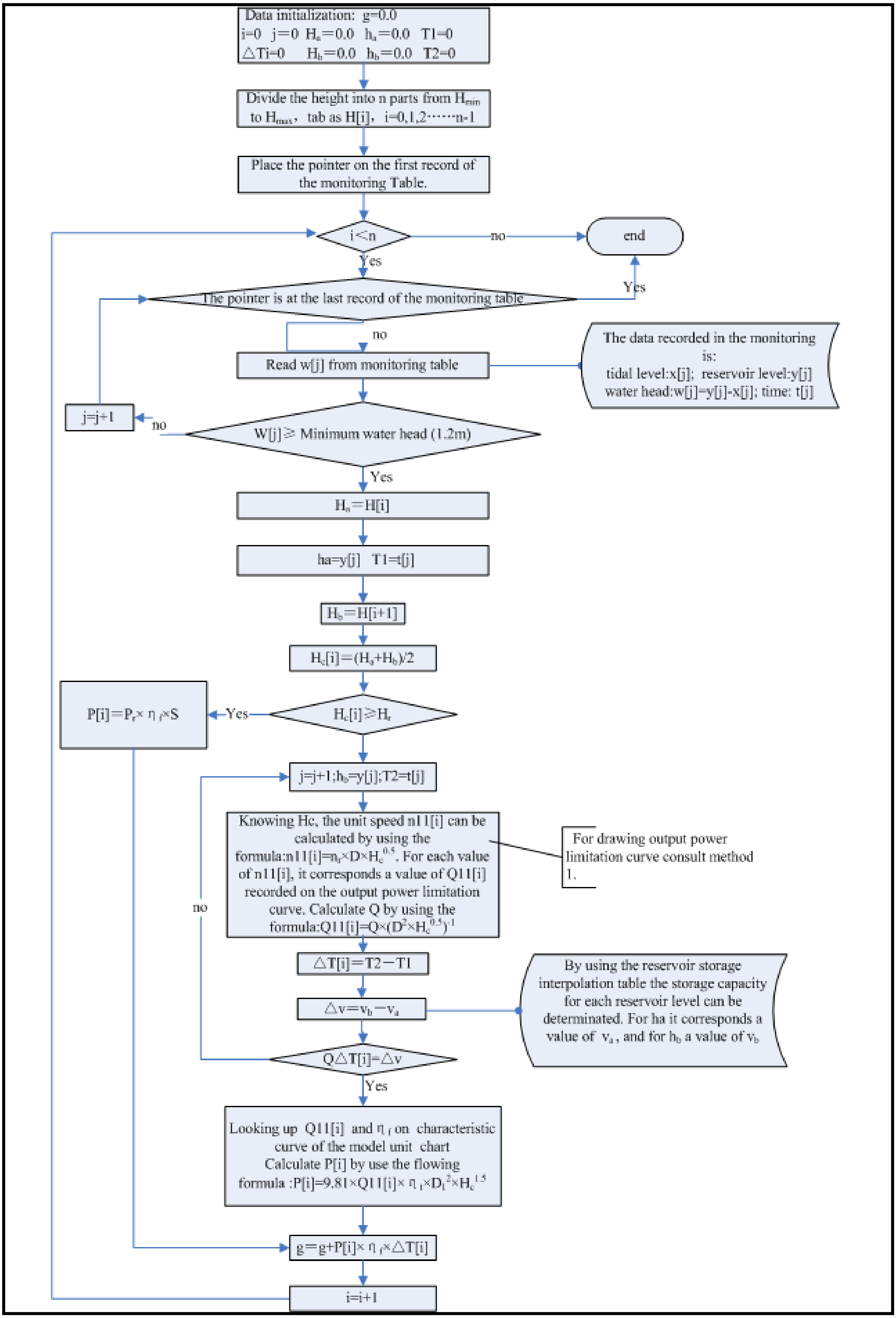


**Fig. 7.2.** Water Head Calculation [XX]

To successfully apply the methods presented, some details have to be taken into account:

- When determining the turbine efficiency through the characteristic curve, the intersection between the lines passing through n11 and Q11 has to be sought. If this point is not over an efficiency curve, it is necessary to interpolate.

- As previously mentioned these methods can be applied for both, one direction and bidirectional turbines, however there is a remark to do concerning the minimum water head. In case of forward turbining, when **W[j]≤Minimum water head (1 m),** there is no power generation, while for reverse turbining, this situation is reached when **W[j ≥ -1 m**; so in the whole, if **-1 ≤ W[j] ≤ 1** there is no power generation.

## 7.3. Testing and results

The methods above outlined where applied to one-direction and two-direction turbines, aiming to determinate which turbine type can generate more power under the same operating conditions. On the following table are displayed the design features for a hydropower generation group working with a minimum water head, $H_{min}$, of 1 meter and a maximum water head, $H_{max}$, of 5.5 m. The runner diameter is 2.5 meter.

On the experiment carried out 6 units were tested, with a generator efficiency, $\eta_f$, of 92% and a design water head, $H_r$, of 3m

| Turbine type | | Single Unit capacity (kw) | Design power | Design efficiency | Design rate speed | Design flow | Max efficiency | Design operating point | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $P_r$ (kw) | $\eta_r$ (%) | $n_r$ (r/min) | $Q_r$ ($m^3/s$) | $\eta_{max}$ (%) | n11 (r/min) | Q11 (L/s) | $\eta_M$ (%) |
| Two-direction | reverse | 497 | 540.22 | 76.17 | 93.8 | 24.32 | 84.26 | 165 | 2247 | 72.3 |
| | forward | 700 | 760.87 | 86.58 | 125 | 31.6 | 89.00 | 220 | 2919 | 83.9 |
| One-direction | forward | 760 | 826.09 | 92.21 | 125 | 31.6 | 94.62 | | | 91.9 |

**Table 7.1.** Design features

Since the objective of the research was to identify which technology generates more power under the same conditions, it has been assumed that the design rate speed, $n_r$, the design flow, $Q_r$, the design water head, $H_r$, and the design operating point (n11, Q11) was the same for both technologies forward turbines.

Bi-direction turbines are design to operate in both directions, ebb and flood mode, therefore their design efficiency is lower than one-direction devices. Moreover, if the characteristics curves, attached in the annex, are regarded, it can clearly be seen that one-direction devices have higher efficiency than bi-directional turbines. It can be noticed from the graphs that one-direction unit`s efficiency ranges between 88 and 94%. While for forward turbining on bi-directional generation, the efficiency is comprised between 80 and 86%, and for reverse turbining the values are range between 68 and 80%.

As for the unit capacity, it appears that for one-direction turbines is higher than forward and reverse turbining in bi-directional devices; the main reason of this difference is that the turbines blades shape are different. Moreover, if the capacity equation is regarded, $P=9.81Q_{11}H^{3/2}D^2\eta$, it can be said that for both types of turbines the water head, H, and the runner diameter, D, are the same; while the water flow, Q11, and the efficiency, η, are different; and what is more, the operation time for both types of turbines is not the same.

On the table also the maximum efficiency is displayed. Although this values are not plot on the characteristic curve, the can be extracted from them.

Before analyzing the results it is important to bear in mind that for one-direction turbines the energy generation takes place as the basin is emptied, i.e., during the ebb current, while bi-directional turbines, produce energy during both, ebb and flood current. It is known that for regular semidiurnal tides, every day there are two ebb and two flood currents.

Following, the table with the results is shown.

| **Turbine type** | | **Generation of one day (KWh)** |
|---|---|---|
| Two-direction | Reverse | 8664.72 |
| | Forward | 11617.29 |
| One-direction | Forward | 12604.15 |

**Table 7.2.** Results

As for the daily generation values obtained for the three operating modes, the highest output is provided by one-direction turbines. Bi-directional devices working in reverse mode produce the lowest output, this is due to the fact that the design efficiency, the rate speed, and the design flow are lower than for forward turbining.

However, if all the energy produced by bi-directional turbines is taken into account, the total energy obtained is 20282.01 MWh/day, whereas for one-direction turbines the daily energy produced is 12604.15 MWh/day, therefore, bi-directional devices produce a 37.85% more energy every day. This fact is because two-directions turbines generate during both ebb and flood flow, thus they generate 4 times a day, twice a day in ebb mode and twice a day in flood mode. On the other hand, one-direction devices can only generate twice a day, twice in ebb mode or twice in flood mode. In our experiment they operate in the ebb mode.

## 7.4. Cost analysis

Finally, a cost analysis has been carried out. The data used on the following assessment belongs to Jangxia Tidal Power Station; therefore, the study is not an average between different plants.

The aim of this analysis is to calculate the levelised costs for both, one-direction and two-direction devices and compare them. The levelised costs are calculated as it is shown in *Eq. 6.1*.

First of all, the investment expenditures have been calculated. The initial investment is constituted by two main costs, construction costs which account the costs of materials, labour, transportation, deployment of the dam, electrical system infrastructure, etc. and devices costs, namely, turbines costs. It is known that on average the turbines costs are around 20 to 40% of the initial investment. Regarding two directions and one direction initial investment, it can be considered that construction costs are about the same for both technologies, however, concerning devices costs, it is known that bi-directional devices are more expensive, around 30 to 50% more than one-direction turbines.

Operation and maintenance expenditures are constituted by the costs related to the devices maintenance as well as the costs related with insurance, salaries, decommissioning, etc. The devices maintenance costs represent 30% of the total operation and maintenance costs; for one-direction turbines these costs are around 10 to 20% of the energy annually produced, while in bi-directional turbines the devices maintenance costs are ranged between 20 to 30% of the energy produced in one year. If the operation and maintenance costs are regarded as a whole, it is considered that for one-direction power plants the maintenance cost of each MWh produced in a year is around 2 RMB, while for bi-directional plants these costs are around 2.6 RMB/MWh. The main reason of this difference is that bi-directional devices require more maintenance, as they have a more complex structure.

Below are shown the equations that reflect the costs considered:

- One direction turbines:

$$\mathbf{I_1 = c_1 + d_1} \quad \text{Eq. 7.1}$$

$$\mathbf{d_1 = 0,3\ I_1} \quad \text{Eq. 7.2}$$

$$\mathbf{M_1 = 2\ x\ E_1} \quad \text{Eq. 7.3}$$

$$\boldsymbol{E_1 = 365\ x\ e_1} \quad \text{Eq. 7.4}$$

- Two- directions turbines:

$$\mathbf{I_2 = c_2 + d_2 = c_1 + 1,4d_1} \quad \text{Eq. 7.5}$$

$$\mathbf{d_2 = 0,3\ I_2} \quad \text{Eq. 7.6}$$

$$\mathbf{M_2 = 2,6\ x\ E_2} \quad \text{Eq. 7.7}$$

$$\boldsymbol{E_2 = 365\ x\ e_2} \quad \text{Eq. 7.8}$$

Where:

- $I_i$: Initial investment
- $c_i$: construction costs
- $d_i$: devices costs
- $M_i$ :Operation and maintenance expenditures
- $E_i$: energy produced annually
- $e_i$: energy daily produced
- i= 1 → One-direction turbine
- i = 2 → Two-direction turbine

In Jangxia Tidal Power Station, 6 bi-directional units work simultaneously. The costs of the first 5 devices installed were around 12000 RMB/KW, while the cost of 6$^{th}$ one was 20000 RMB/KW, thus, the devices costs are calculated as it follows:

$$d_2 = \frac{5\ x\ 12000 + 20000}{6} = 13333{,}3\ RMB/KW$$

Once the devices costs are known, the initial investment, $I_2$, and the capital costs, $c_2$, can be calculated:

$$\mathbf{I_2 = 44444.4\ RMB/KW}$$

$$c_2 = 0,7\, I_2 = 46666.7\ RMB/KW$$

Moreover, the current installed capacity has been calculated considering the capacity of each of the 6 units.

$$Installed\ capacity = 500 + 600 + 3\ x\ 700 + 700 = 3900\ KW \qquad \text{Eq. 7.9}$$

A

As the levelised costs are going to be calculated, the initial investment costs needs to be express in RMB.

$$\boldsymbol{I_2 = 44444,4\ \frac{RMB}{KW} x\ 3900\ KW = 173,333,333\ RMB}$$

From the initial investment, construction costs and devices costs expressed in RMB can be calculated.

$$c_2 = 0,7\, I_2 = 121{,}333{,}333.3\ RMB$$

$$d_2 = 0,3\, I_2 = 52{,}000{,}000\ RMB$$

Once two-direction turbines costs are calculated, one-direction devices initial investment can also be calculated, as their costs are related.

$$c_1 = c_2 = 121{,}333{,}333.3\ RMB$$

$$d_1 = \frac{d_2}{1,4} = 37{,}142{,}857\ RMB$$

$$\mathbf{I_1 = c_1 + d_1 = 158,476,190\ RMB}$$

Following, maintenance costs have been calculated from the values of daily generation. To calculate maintenance costs for one-direction turbines, the values used for the energy produced annually are the ones obtained after testing the devices; whereas for bi-directional devices two different values of annual energy have been considered; on the one hand, the values obtained after testing the devices have been used while on the other hand it has been considered that the energy produced is 6500MWh/year, average annual production, consequently two different values for maintenance costs have been obtained.

- One-direction turbines:

$$E_1 = 365\ x\ \ 12605.15 = 9{,}201{,}029.5\ KWh$$

$$\mathbf{M_1\ =\ E_1\,x\,2\ \frac{RMB}{KWh} = 19,247,627.5\ RMB}$$

- Two-directions turbines:

$$E_2 = 365\ x\ \ (11617.29 + 8664.72) = 7{,}402{,}933.65\ KWh$$

$$\mathbf{M_2\ =\ E_2\,x\,2,6\ \frac{RMB}{KWh} = 19,247,627.5\ RMB}$$

$$E_2\ = 6{,}500{,}000\frac{KWh}{year}$$

$$\mathbf{M_2\ =\ E_2\,x\,2,6\ \frac{RMB}{KWh} = 16,900,000\ RMB}$$

.

Furthermore, the savings in fuel have been calculated. For every KWh produced by burning fuel some emissions are released to the atmosphere, thus contributing to the environmental pollution. Fuel costs are calculated as shown:

$$F_t\ = CO_2 +\ NO_X + SO_2 \qquad \text{Eq. 7.10}$$

On the following table are displayed the emissions emitted by a thermal plant; as well as the costs per ton emitted. The fuel savings are calculated from this data.

| | **Emissions (Kg/KWh)** | **Costs (RMB/ton)** |
|---|---|---|
| **$CO_2$** | 0.81 | 291.556 |
| **$NO_X$** | 0.002467 | 4000 |
| **$SO_2$** | 0.0028 | 1500 |

**Table 7.3.** Emissions emitted and emission costs

- One-direction turbines:

$$CO_2\ = 0{,}00081\ \frac{T}{KW\ h}\ x\ 4{,}600{,}514.75\ \text{KWh x } 291.556\ \frac{\text{RMB}}{\text{Ton}} = 1{,}086{,}459.22\ \text{RMB}$$

$$NO_X = 0{,}000002467\ \frac{T}{KW\ h}\ x\ 4{,}600{,}514.75\ \text{KWh x }4000\ \frac{\text{RMB}}{\text{Ton}} = 45{,}397.88\ \text{RMB}$$

$$SO_2 = 0{,}0000028\ \frac{T}{KW\ h}\ x\ 4{,}600{,}514.75\ \text{KWh x }\ 1500\ \frac{\text{RMB}}{\text{Ton}} = 193,221.62\ \text{RMB}$$

$$\boldsymbol{F_{1t} = 1,325,056.36\ \text{RMB}}$$

- Two-direction turbines:

$$CO_2 = 0{,}00081\ \frac{T}{KW\ h}\ x\ 6{,}500{,}000\ \text{KWh x }291.556\ \frac{\text{RMB}}{\text{T}} = 1{,}535{,}010.75\ \text{RMB}$$

$$NO_X = 0{,}000002467\ \frac{T}{KW\ h}\ x\ 6{,}500{,}000\ \text{KWh x }4000\ \frac{\text{RMB}}{\text{T}} = 64{,}412\ \text{RMB}$$

$$SO_2 = 0{,}0000028\ \frac{T}{KW\ h}\ x\ 6{,}500{,}000\ \text{KWh x }\ 1500\ \frac{\text{RMB}}{\text{T}} = 273{,}000\ \text{RMB}$$

$$\boldsymbol{F_{2t} = 1,872,152.75\ \text{RMB}}$$

Once all the costs are known, it only remains to fix the value of the discount rate and the life of the system. In China the discount rate is ranged between 7% and 10%, for this reason, both values have been considered. Concerning the life of the system, several values have been deemed, 20, 30 and 40 years, as Jiangxia Tidal Power Plant has already been correctly operating for 20 years and almost reaching 30 now. Moreover, it is predicted that continues operating for a few more years.

For the levelised costs calculation it has been considered that the first year that the plant operates, the operation and maintenance costs will only be 70% of total maintenance expenditures. This 70% corresponds to the costs related with salaries, insurances, etc. due to the fact that during the first year of operation the devices will not need maintenance. The initial investment has only been considered on the first year, because once the plant is deployed, only maintenance costs will remain. Fuel savings have been considered all the system life, because they are present since the plant starts to operate.

Finally the levelised costs have been calculated; following, the results are shown.

**One-direction turbines**

| Project life, n | Discount rate, r | Energy, E (MWh/year) | LCOE (RMB/MWh) | LCOE (£/MWh) |
|---|---|---|---|---|
| 20 | 0,07 | 4600,51 | 4697,92 | 442,14 |
| 30 | 0,07 | 4600,51 | 4261,18 | 401,04 |
| **40** | **0,07** | **4600,51** | **4104,68** | **386,31** |
| 20 | 0,1 | 4600,51 | 5326,26 | 501,28 |
| 30 | 0,1 | 4600,51 | 4976,08 | 468,32 |
| 40 | 0,1 | 4600,51 | 4858,54 | 457,26 |

**Table 7.4.** One direction turbines LCOE

**Two- directions turbines**

| Project life, n | Discount rate, r | Energy, E (MWh/year) | LCOE (RMB/MWh) | LCOE (£/MWh) |
|---|---|---|---|---|
| 20 | 0,07 | 6500 | 4595,65 | 432,51 |
| 30 | 0,07 | 6500 | 4261,62 | 401,08 |
| 40 | 0,07 | 6500 | 4126,68 | 388,38 |
| 20 | 0,1 | 6500 | 5076,19 | 477,74 |
| 30 | 0,1 | 6500 | 4808,37 | 452,53 |
| 40 | 0,1 | 6500 | 4718,48 | 444,08 |
| 20 | 0,07 | 7402,93 | 4343,84 | 408,82 |
| 30 | 0,07 | 7402,93 | 4051,78 | 381,33 |
| **40** | **0,07** | **7402,93** | **3933,8** | **370,22** |
| 20 | 0,1 | 7402,93 | 4764,01 | 448,36 |
| 30 | 0,1 | 7402,93 | 4529,85 | 426,32 |
| 40 | 0,1 | 7402,93 | 4451,25 | 418,92 |

**Table 7.5**. Two- direction turbines LCOE

From the values obtained, it can be concluded that the longer the life of the system is, the lower the energy cost is. It is a reasonable remark because the longer a plant runs, the more profitable it is, and consequently, lower is the cost of electricity.

On the other hand, if the discount rate is considered, it can be said that the lower it is, the lower the energy cost is. This is because a lower discount rate means lower risk and therefore, lower capital cost.

On the following graphs are shown the effect of both, the discount rate and the system life.

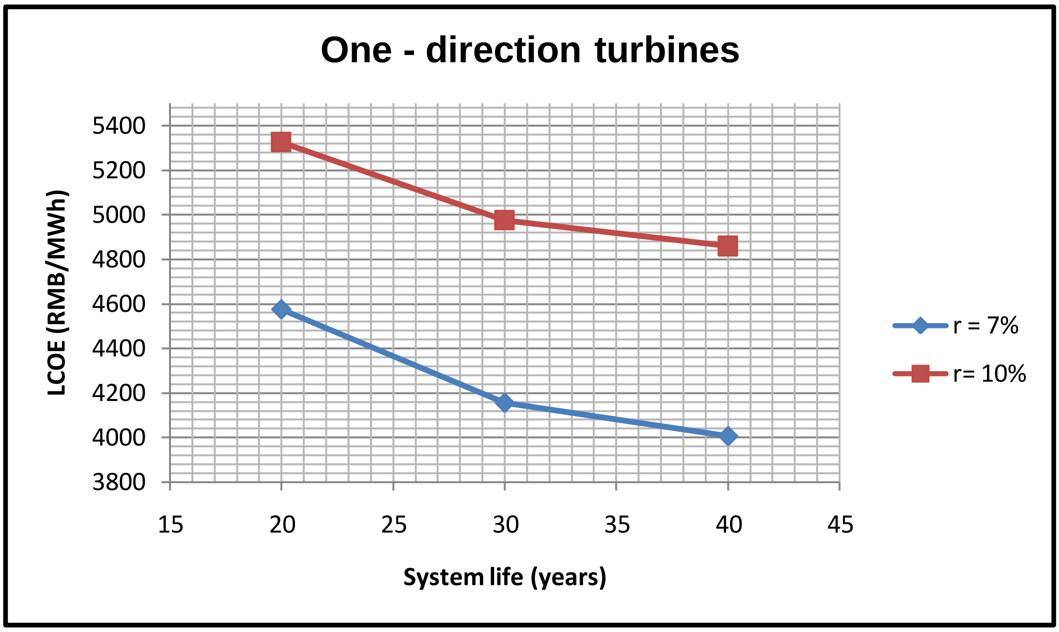


**Fig. 7.3.** : LCOE versus System life for one-direction turbines

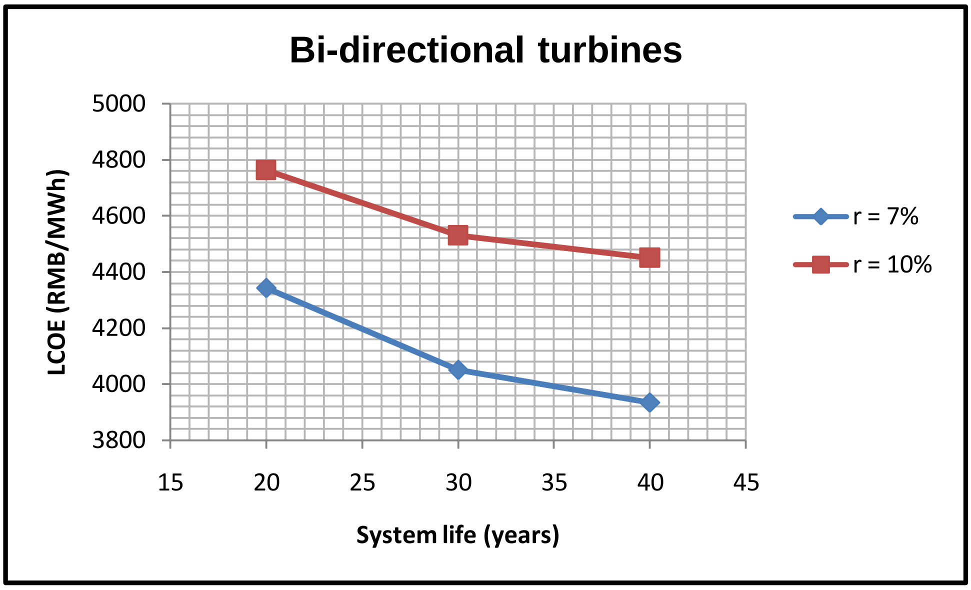


**Fig. 7.4.** : LCOE versus System life for bi-directional turbines

Finally, if we compare the LCOE values obtained for both technologies, it can be firmly conclude that bi-directional technology presents a lower energy cost. For this reason, it can be said that the extra cost that the bi-directional devices hold is compensate with the extra energy generated.

On the following graph are plotted the values of the LCOE's for both technologies.

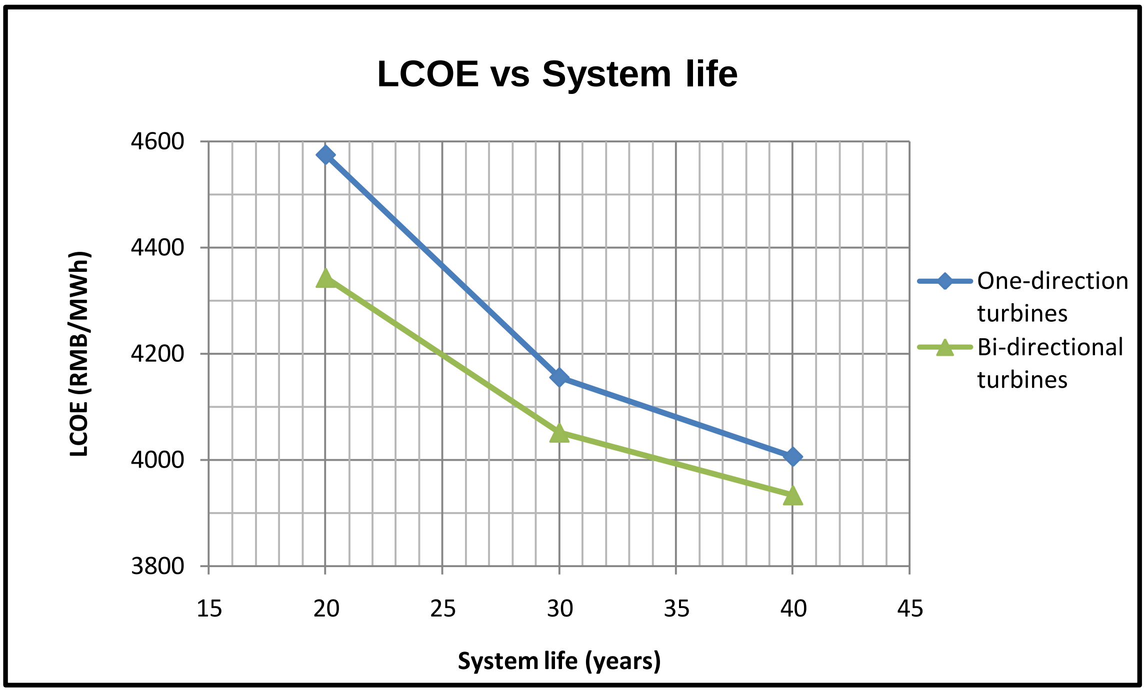


**Fig. 7.5.** LCOE versus System life for both technologies

It has to be commented that for bi-directional devices, the values of LCOE plotted on the graphs correspond to the ones calculated considering the annual production obtained on the experiment, 7402.93 MWh/year. This value of energy production is more accurate, because the other one, 6500 MWh/year, is just the average production of one year, and the production changes from year to year. Moreover, as for one-direction turbines the values of the experiment are used, it is also more reasonable to use them for bi-directional devices.

# 8. Conclusions

Tidal power, is a clean and renewable source of energy and has the advantage of predictability over other renewable sources, tides can be predicted years in advance.

The high capital costs of tidal barrage are likely to restrict their development; however its deployment can bring several benefits. On the one hand, the dam acts as protection against floods, on the other hand, it permits connection between both sides of the dam, acting as a bridge, allowing transportation. Moreover, it can bring benefits such as improvement in aquacultures. Furthermore, as previously mentioned it has some environmental benefits, for instances marine life may flourish at sites where they are not normally found; but it also has some environmental impacts as it causes changes on the estuary ecosystem, as well as silt accumulation behind de barrage, however with careful barrage design and operation and with limited dredging for maintenance silt movement need not to be a problem. It can also have negative effect on migratory species. All in all, although some environmental uncertainties remain and require more investigation, operational experiences have generally been positive, given that not big environmental constraints that could inhibit wide implementation of the technology have been identified.

Concerning the technologies used in a tidal barrage, from our study it can be concluded that although one-direction turbines produce more power than forward turbining and reverse turbing in bi-directional devices, all in all, the total energy produced by bi-directional devices in one day is higher due to the fact that they generate energy during both, ebb and flood current. It has also been shown that bi-directional devices present a lower energy cost. Therefore, the extra-power generated by these devices, compensates the extra costs that the technology holds. However, these conclusions are valid for the scope of our study, Jiangxia tidal power, to generalize further investigation should be conducted.

Tidal current devices have lesser impact on the environment than tidal barrages. However the full extent of the environmental impacts still unknown; nonetheless what is known is that they cause a very low noise and visual impact. A clear benefit of these devices is their high power density, due to the fact that to produce a certain output the turbines needed are much smaller than in wind industry. Moreover, as this technology stills in its infancy, it present very high costs, however it is predicted that they will considerably decrease; anyhow, it will present high maintenance and power distribution costs.

Another issue to consider concerning tidal stream is grid-connection. It has already been demonstrated that it is technically possible, however, the number of sites where both, tidal stream energy resource exists and it is possible to grid-connect is limited. For this reason, the growth of this technology is highly dependent on the ability to connect to the grid. Due to the high costs concerning tidal stream initial farms, it is unlikely that network reinforcements would be done in the short-term, therefore, this may restrict the capacity of initial farms and/or the number of initial developers. However, it is expected that in the long term several upgrades will be done to overcome capacity constraints.

A clear benefit that both technologies present towards other conventional technologies is that they are an alternative to fossil fuels. The increase on fossil fuels prices is leading to a high base cost of electricity which would bring forward the time when tidal power becomes cost-competitive and reduces the necessary costs of support. Moreover, as the installed capacity of tidal generation increases it will displace conventional generation which has an impact on the emissions; therefore, tidal technology is considered strategic within the energy mix. The potential for carbon emission reduction should also be seen in a strategic context as well as environmental. Another reason why tidal energy is becoming an increasingly favorable alternative to conventional energy resources is that increases security of supply due to its predictability; it also offers innovation potential, broadens industrial capabilities and assists with economic development through employment and manufacturing.

However a drawback to remark in contrast to their predictability is the intermittent power generation which has implications for large scale grid integration. In the day to day operation, conventional generation units are required to cycle in order to meet demand. This cycling has some costs associated such us additional operation and maintenance with increasing overhauls, higher heat rates due to low load and variable operation, moreover, more fuel is needed, mainly during start up.

Bearing in mind all the mentioned points, it can be said that tidal power has a great potential, for this reason, it is necessary to set some mechanisms to assist the development of the technology. Following some possible tidal energy policies are presented.

- **Financial and tax incentives**

  It consists on providing the costs reductions that tidal energy technologies require to become competitive with conventional systems. Some incentives could be tax credits, reduction in income tax, loans and rebates, etc. Moreover, to reduce the risk of investing in tidal energy technologies, subsidy payment per unit of electricity produced should be given to electricity suppliers.

- **Research and development funding**

R&D is needed to promote the development of the technology. The quantity of funding for tidal research determines the speed of cost reduction of these technologies. R&D is carried out between universities and public institutions or private companies. For tidal current technologies in particular, demonstration programs can play a crucial role in testing the performance and reliability of new immerging technologies.

- **Feed-in tariff**

The purpose of this mechanism is to encourage the development of renewable energy technology since purchasing renewable electricity is more expensive than conventional energy. Feed-in-tariffs are the best method to develop renewable energy technologies as it provides a stable and profitable market. The tariff level varies from country to country. If feed-in-tariffs are well structured, future stability for tidal energy companies can be granted.

- **Carbon tax**

This mechanism is an environmental tax which applies on $CO_2$ and other green house emissions. It is effective on the combustion of fossils fuels; moreover, implementing it serves as an incentive for all renewable energy technologies.

- **Mandatory renewable energy targets**

This mechanism requires a fixed percentage of electricity to be generated from renewable energy, every time more, is becoming more popular in most developed countries; and it has shown considerable development worldwide so far.

- **Improvements in planning process**

One of the barriers on tidal energy development are the problems related to planning. For this reason, the aim of this mechanism is to make the regional authorities aware of the importance of renewable energy and strategic energy planning which is conducted at local, regional and national level to insure that planning issues are dealt with swiftly and in a consistent manner.

To sum up, effective tidal energy policies are critical to the development of tidal energy. If these policies are well structured and implemented tidal energy can play a vital role in a sustainable energy future.

# ANNEX

## CALCULATION METHOD

The calculation method defined on “JIANG XIA CHAO XI SHI YOU DIAN ZHAN” book, from which the methodologies used to determinate the energy produced have been developed, is shown. The original document is in Chinesse, for this reason an English version has been attached.

It has to be mentioned that for backward turbining the process used to determinate the electric energy produced is exactly the same, however, in this case, the figure obtained is symmetric to *Fig A.1.*, with the x axis as the symmetric axis.

1. - At **t1** moment, the unit begins the forward turbining. Before this moment, reservoir level **h1** stays constant, as shown in *Fig A.1.* At **t1** instant, the water head, difference between reservoir and tidal level, is **H1**.

2. - After a period of time, **Δt1, t2** instant is reached. At that moment, the reservoir level is **h2** and the water head is **H2**.

3. - For the period of time **Δt1,** the average water head **H** can be determinate according to the following equation:

$$\mathbf{H = \frac{H_1 + H_2}{2}} \qquad \text{Eq. A.1}$$

4. - Knowing the average water head **H**, the runner diameter D and the unit discharge Q11, the average flow discharge Q can be calculated through the following formula:

$$\mathbf{Q = Q_{11} D_1^2 \sqrt{H}} \qquad \text{Eq. A.2}$$

Where:

- Q: average flow discharge

- $Q_{11}$: unit discharge;

- $D_1$: Runner diameter

- H: water head

5. - According to *Fig A.2.*, the variation of the reservoir storage capacity **ΔV1** during the period of time **Δt1** can be determinate using **h1** and **h2**.

6. - At this stage, the value of the three parameters, **Q,** **Δt1** and **ΔV1**, are known. The reservoir storage capacity variation, **ΔV1,** during a period of time **Δt1** has to be compared with the flow discharge **Q** flowing through the reservoir during **Δt1.** If the two values, **Q·Δt1** and **ΔV1** are not equal, **h2** has to be changed for the period of time **Δt1**. Steps from 2 to 5 have to be repeated until both terms are equal. Once **h2** correct value is achieved, **H2** can be determinate.

7. - Once the moment **t2** is known, the period of time **Δt1** is determinate, consequently, the average water head, **H,** can be calculated. At this stage, with the average water head **H** and the characteristic curve, the average power **P** for the period of time **Δt1** can be determinate, using the following formula.

$$P = 9.81 \times Q_{11} \times \eta_t \times D_t^2 \times H_c^{1.5} \qquad \text{Eq. A.3}$$

8. - Electric energy produced, **W1,** during the period of time **Δt1**, can be calculated through the following formula:

$$W_1 = P\,\Delta t_1 \qquad \text{Eq.A.4}$$

9. - To determinate the electric energy production, **W,** at each period of time **Δt2, Δt3,** etc. the process above has to be repeated until the positive electric energy production is ended. For bi-directional turbines the same method can be applied, but in this case when the positive electric energy production ends, the negative energy production starts.

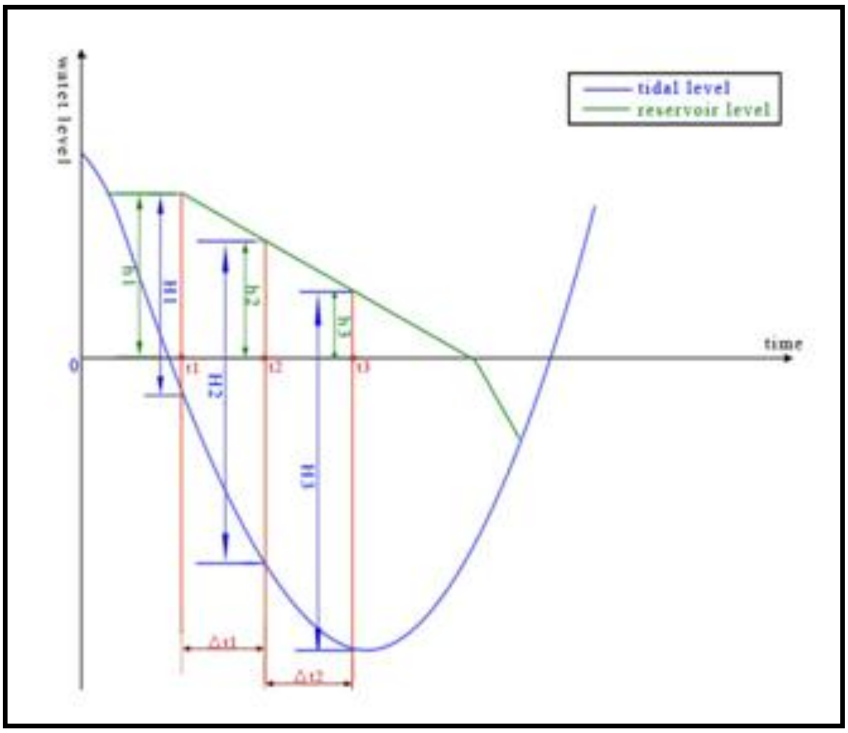


**Fig. A.1.** Positive energy production [XXI]

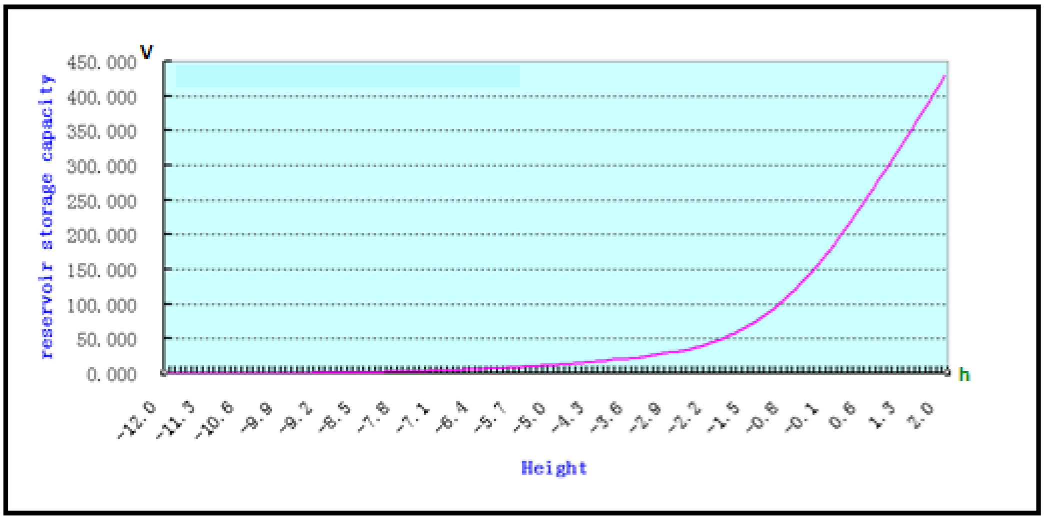


**Fig. A.2.** Reservoir storage capacity curve [XXI]

ONE DIRECTION TURBINE’S CHARACTERISTIC CURVE

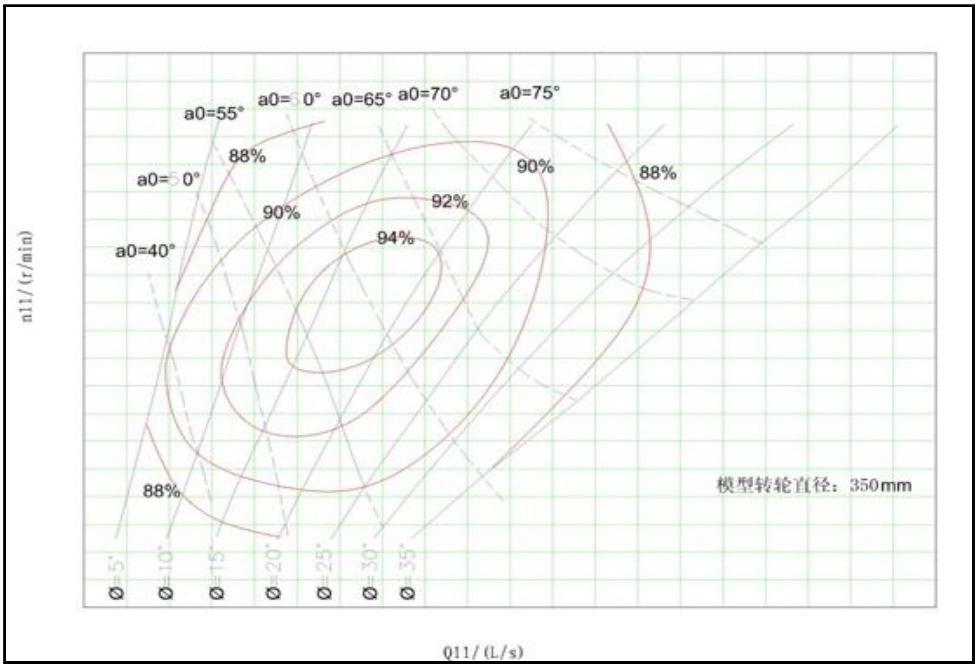


**Fig. A.3.** One direction turbine’s characteristic curve [XX]

BIDIRECTIONAL TURBINE’S CHARACTERISTIC CURVE

- Positive direction

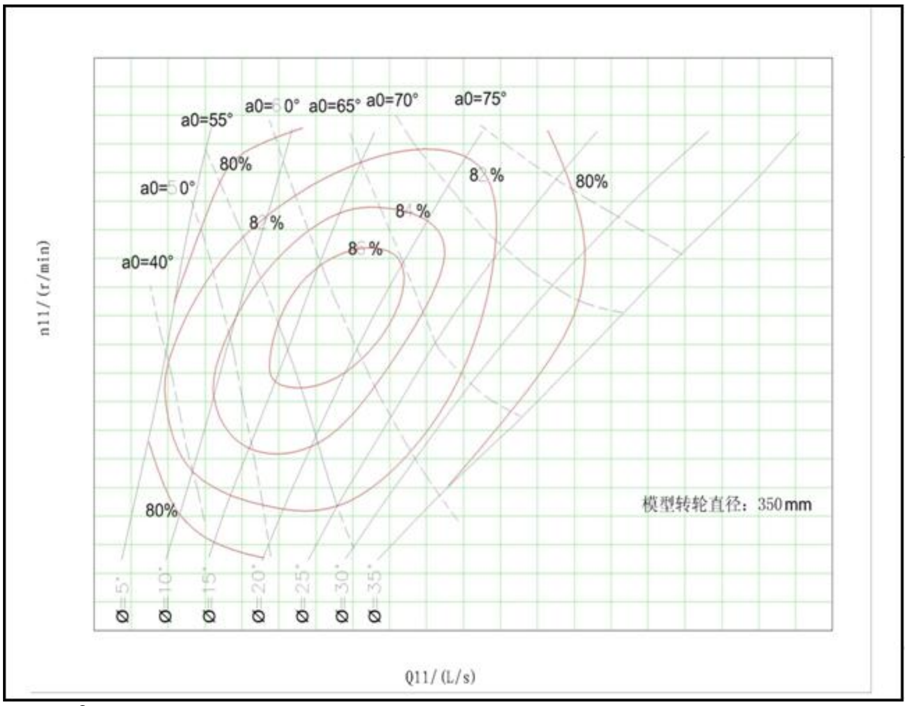


**Fig. A.4.** Bidirectional turbine characteristic curve, positive direction [XX]

- Reverse direction

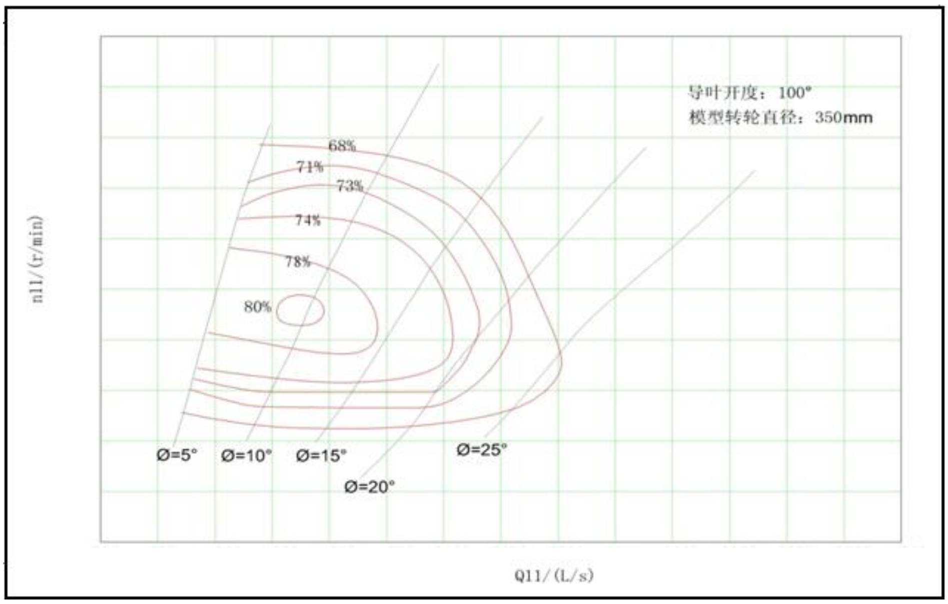


**Fig. A.5.** Bidirectional turbine characteristic curve, reverse direction [XX]

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