

## Dutch results of Pro-Tide; an NWE-Interreg project on Developing, Testing and Promoting Tidal Energy in coastal and estuarine zones

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### ABSTRACT

Pro-Tide's mission is to Develop, Test and Promote Tidal Energy in coastal and estuarine zone. Within the wide spectrum of Tidal Power applications, the Dutch project is specifically targeted at Low Head Tidal and River Hydropower, for conditions as found in the Brouwersdam project (typically 1 meter head, thousands of m<sup>3</sup>/s), and also in Delta rivers. In addition to the challenge how to join forces between Public and Private Partners, (PPP), the Dutch project specifically focuses on searching, finding and selecting the Best Available Technique (BAT), tests and demonstration this technology.

The Best Available Technique is identified by an independent, purpose targeted R&D-advisory board, using a Multi Criteria Analysis (MCA). The first step involves a worldwide technology scan, condensed in factsheets, covering 10 categories and providing a comprehensive overview of available techniques. The subsequent MCA utilizes selection criteria, ranging from Levelized Costs of Energy (LCoE) to Fish Friendliness.

The best techniques identified in the MCA are now being tested for performance and fish friendliness. The first test results which are very relevant for future application will be presented, also in conjunction with economic parameters.

In the presentation, the process of identifying and selection the Best Available Technique will be outlined. The overview and ranking of techniques will be presented, with considerations why a technique is, in more or less extend, suitable for application in Ultra Low Head Tidal- and River Power systems.

Overall, the paper and presentation will provide a clear overview and, in addition, a targeted- and quantitatively tested selection of Ultra Low Head Tidal and Delta River Power techniques.

*Keywords:* Pro-Tide, Interreg-NWE, Ultra Low Head Tidal Techniques.

### 1. INTRODUCTION

Given the current state of technology, two critical success factors dominate successful application of low head hydropower: 1) Costs and 2) Fish Friendliness.

Regarding costs, several studies (see e.g. MIRT, 2011) have shown that at present the limit of economic viability of low head hydropower systems lies somewhere around 3-4 meter head. The underlying principle is that the lower the head, the larger the machines must be to generate a certain amount of power. As costs are associated with size (and weight) of machinery and civil constructions, energy generated from a low head systems tends to be more expensive than energy generated from a high head system. To that end, when mentioning "ultra low head hydropower", reference is made to conditions as found in the Dutch Brouwersdam project: 1 meter head @ roughly 2500 m<sup>3</sup>/s flow rate on average.

Regarding fish friendliness, it is known that standard low head technology (as applied in low head river power plants in the main Dutch rivers) is fish unfriendly. For downwards migrating Silver Eel for example, test results in Linne power plant show a mortality rate of 10-20 % per passage, depending on the flow rate (position of the guide and rotor-blades). This mortality rate is judged too high to support a sustainable population of the species in the Dutch waters. For Tidal Power plants the situation is even more precarious as with the back and forward moving tide, fish may be subjected to multiple passages. It is therefore that the Ministry of Infra Structure and Environment now sets strict targets of fish mortality at a level of < 0,1 %, which is unprecedented by current technology.

Both aspects (costs and fish friendliness) point toward the need for innovative solutions. This has been recognised by the Pro-Tide-NL projects partners, and it was decided to seek for new technology that could improve both costs-effectiveness as well as fish friendliness of low head hydropower.

As will be outlined in this paper, the quest for improved technology is done in a stepwise manner:

1. A Technology Inventory is made of all known techniques for conversion of low head hydropower. Criteria for incorporation in the inventory was that the technique must be proven at least on small scale, in the laboratory. Twenty representative technology examples have been documented in Technology Factsheets. The techniques have been categorised based on the physical principle for hydro-electric conversion.
2. Implementation of a Multi Criteria Analysis (MCA). To identify the Best Technique, the categories have been ranked according to critical success factors "criteria", with an individual weighting factor.
3. Implementation of an R&D-advisory board, comprising experts on relevant disciplines (technology, morphology, ecology and legislation). Experts are invited on personnel title and are independent (not associated with market parties). Input from the non-governmental side is organised by inviting 3 external experts in the field to give their opinion about the procedure, the techniques and the selection procedure.

This paper will follow the step-wise approach that was pursued in the identification of the Best Available technique: It will address the search for new technology, synthesised in technique categories and documented in Technology Factsheets. Subsequently the MCA-analysis will be outlined. The organisation of the R&D-advisory board is presented and, the board's advice is formulated, together with considerations. This paper will close with an outlook for further research.

## **2. SEARCHING & FINDING: TECHNOLOGY FACTSHEETS AND CATEGORIES**

### 2.1 Inventory: Technology Factsheets

To facilitate the selection of the Best Available Techniques, a scan was made of unique techniques for conversion of ultra low head hydro power, in electricity. Basic criterion for entering the list is that the technique must be demonstrated, at least in a laboratory: Conceptual systems are considered to be pre-mature and certainly not ready within an acceptable time limit (<5 years).

The search for techniques was done by Pro-Tide-NL's Technical Coordinator on the basis of literature research, Internet research and contacts with Pro-Tide partners (WenZ<sup>1</sup> and Dover Harbour), manufacturers and technology suppliers. It started right at the beginning of the Pro-Tide project in May 2013 and a first version of the inventory was presented at the WP1 Masterclass in Antwerp. The inventory is incorporated in the WP1's report on technology (Goormans, 2013).

The results of the technology scan are reported in the form of Technology Factsheets, with every technique (manufacturer, make) on one A4-page. The Technology Factsheets give a short description of the technique and also reports the main performance criteria: Technology, Ecology and Economy, see Berkel (2014).

### 2.2 Inventory: Category Overview

Figure 2.1 gives the category overview, which was distilled from the technology inventory, as represented in the Technology Factsheets.

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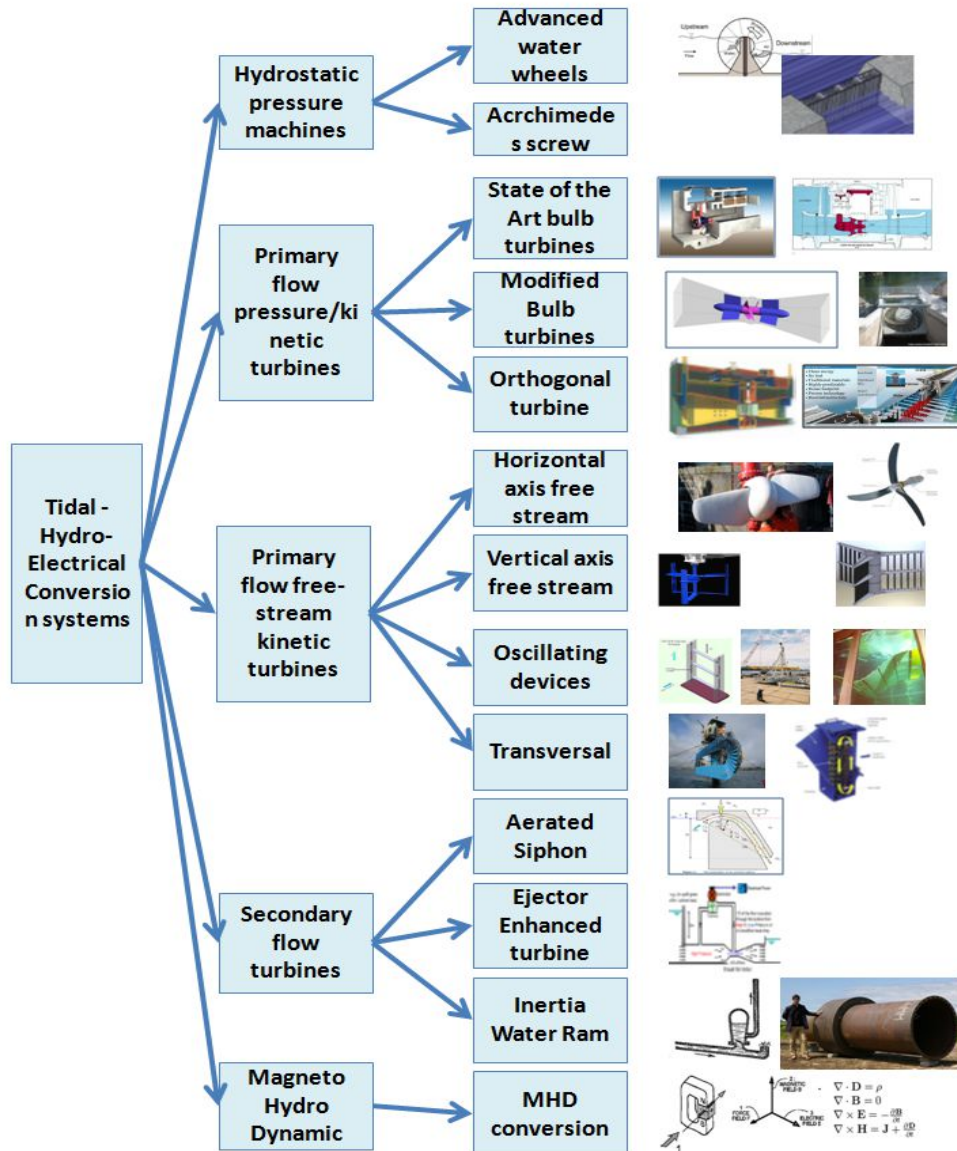


Figure 2.1 Ultra Low Head technique's topology, Berkel (2014).

The category overview gives overarching categories (mostly non-manufacturer specific), that will be evaluated in the MCA-analysis.

### 3. MCA-PREPARATION

#### 3.1 MCA-table: criteria and weighting factors

The Multi Criteria Analysis tool was selected right from the beginning of the project and a first version was presented at Pro-Tide's WP1's Master class held in Antwerp, in May 2013, see table 3.1 and Goormans (2013).

Table 3.1. Criteria and weighting factors at the start of Pro-Tide, May 2013.

Criterion (May 2013)	Weighting factor [%]
kWh-costs	30
Fish Friendliness	30
Proven technology	20
Export Ability	10
Innovation	5
Pump function	5

All criteria to be awarded with scores between 0 (very bad) to 4 (Excellent).

The audience participating in the master class WP1 in Antwerp ( Pro-Tide partner meeting in May,2013) was invited to add criteria, of which a further selection was made. The additions made during the master class were categorised and labelled according to the main important aspect. The tentative MCA-table was further evaluated by the Dutch R&D-advisory board. Partly bearing the Brouwersdam project in mind, the board modified the criteria and weighting according table 3.2.

Table 3.2. Final list of criteria and weighting factors, May 2014

<b>Criterion (May 2014)</b>	<b>Weighting factor [%]</b>
kWh-costs	30
Fish Friendliness	30
Technology Readiness	25
Energy Yield	10
Export Ability	5

Regarding the criteria for successful application of ultra low head tidal systems, the following remarks can be made:

#### **kWh-costs**

kWh-costs of Hydro Power Plants (HPP) are governed by two main components:

1. Annual yield (GWh), mainly determined by generating efficiency, average head tidal across the dam (related to tidal fluctuation) and flow rate.
2. Costs for building the power plant (both machinery as well as civil construction) and Operation and Maintenance (O&M)

In absence of fuel costs, investments costs put a heavy burden on the kWh-production costs of sustainable electricity generation plants. To discern between hydro-electrical generation options (as meant here), the costs per kWe installed power are of prime importance.

#### **Fish friendliness**

Estuarine and delta river ecology is valuable and strict thresholds for allowable mortality for fish and sea mammals are set. The current criterion in The Netherlands is 0,1 % allowable mortality for fish, for a single passage.

Fish friendliness (and regarding sea mammals and humans) is an important criterion. Techniques that are proven to be very fish unfriendly are knocked out immediately, techniques that are proven fish-friendly deserve a score 4. Techniques with unknown fish friendliness, are evaluated on the basis of expert-experience with a gradual score between 0 and 4.

#### **Technology Readiness (incl. Innovation)**

Technology Readiness Levels can be expressed in various ways. As an example, here the TRL-scale of the US-Department of Energy (DoE) is adopted, modified to an MCA-score 0-4: where "0" indicates: "The basic components are integrated so it can be tested in a simulated environment. Examples include laboratory integration of components", and "4" relates to: "Actual application of technology is in its final form - Technology proven through successful operations".

The Technology Readiness criterion has a relation with the Innovation criterion that was originally part of the MCA criteria.

#### **Energy Yield**

Reflects the ambition to substantially contribute to production of sustainable electricity. It is directly related to efficiency in a technical sense: The amount of electricity produced for a certain hydropower potential. The spectrum is spanned by high efficiency systems (overall 70-80 %) to low efficiency systems (5-10 %).

#### **Exportability**

Low Head Tidal and River Power typically is a Delta Technology and perfectly suits the Dutch strong export position in marine technology, dredging, off-shore technology and Water management. Export is the main legitimisation of the development for the Netherlands as its own national tidal & hydropower potential is modest (1-2 %). Note that the criterion exportability score is in a practical sense binary: The technique is either developed (patented, manufactured) in the Netherlands, or it is not.

#### **Other aspects**

Other important aspects like Morphology and Legislation are incorporated implicitly in the MCA. It must be noted that these aspects do not directly strongly discriminate between hydro-electric conversion options.

Also note that the criterion Pump Function, which was present in the original MCA criteria, was left out in the final list. In the original set-up, Pump Function was meant in the sense of discharge capacity of excess river effluent against high North Sea Level, which for the Brouwersdam no longer is judged desirable on the short term (< 30 years). Pump Function as a means to increase power generation still is incorporated in the MCA via the kWh-costs and Energy Yield criteria.

### 3.2 Final MCA-table

The Multi Criteria Analysis tool was identified right from the beginning of the project. On the basis of the Technology Categories (figure 2.2), the technology Factsheets, the Selection Criteria and Weighting Factors, the MCA table follows:

Table 3.3. Multi Criteria Analysis table, version April 17, 2014.

<b>Pro-Tide NL: Multi Criteria Analysis. 17-04-2014</b>						Excellent	4
Low Head HydroElectrical Conversion Techniques						good	3
						fair	2
						bad	1
						Very bad	0
Variable	kWh-costs	Fish Friendliness	Technology Readiness	Energy Yield	Exportability	Total	
Weighting factor [%]	30%	30%	25%	10%	5%	100%	
<b>Modified Bulb</b>							
<b>Orthogonal Turbine</b>							
<b>Free Stream (HAWT + VAWT)</b>							
<b>2nd medium: VETT</b>							
<b>Hydrostatic Wheels &amp; Screws</b>							
<b>Bulb turbine</b>							
<b>2nd medium: Aerated Siphon</b>							
<b>Oscillating Devices</b>							
<b>Magneto Hydro Dynamic</b>							
<b>Transversal Machines</b>							
<b>Inertia Water Ram</b>							

Above MCA table was used in the identification of the Best Available Technique by the R&D-advisory board and the external experts. Note that the technology categories correspond with the categorisation shown in figure 2.1.

## 4. SCORING THE MCA, RANKING THE OPTIONS

### 4.1 The Jury: R&D Advisory Board and experts in the field

From the onset of the Pro-Tide project it was felt that selection of the Best Available Technique needed to be done by an sovereign body: An advisory board consisting of experts from independent (governmental) institutions. Following this principle, all members of the advisory board are invited on personal title, independent from the private sector (manufacturers) and selected for their specific complementary expertise. It is the R&D-advisory board's responsibility to:

- a) Verify the technology inventory regarding completeness and adequate documentation in Technology Factsheets.
- b) Set the Multi Criteria Analysis: Identify the criteria and weighting factors
- c) Evaluate all responses and finally,
- d) Formulate the R&D-advice.

It must be acknowledged here that the selection procedure and the selection of the BAT itself is the collective responsibility of the entire board.

For incorporation of non-governmental knowledge and expertise, also three external experts were invited to rank the technique categories identified in the technology inventory. The personnel composition of the advisory board and the expert panel can be found in Berkel (2014).

Within the timeframe of 3 meetings, the advisory board members and field experts ranked the technology categories, outlined in figure 2.2, thereby using the MCA-table 3.2 and procedure described.

By using the MCA-method, synthesis was a straight forward exercise: All (10) MCA-tables of the 7 R&D-Advisory Board members and the 3 External experts were averaged to give the final result.

#### 4.2 Two Ratings: "Full scale" and "Light"

Rating for the Best Available technology is done for two configurations, see figure 4.1

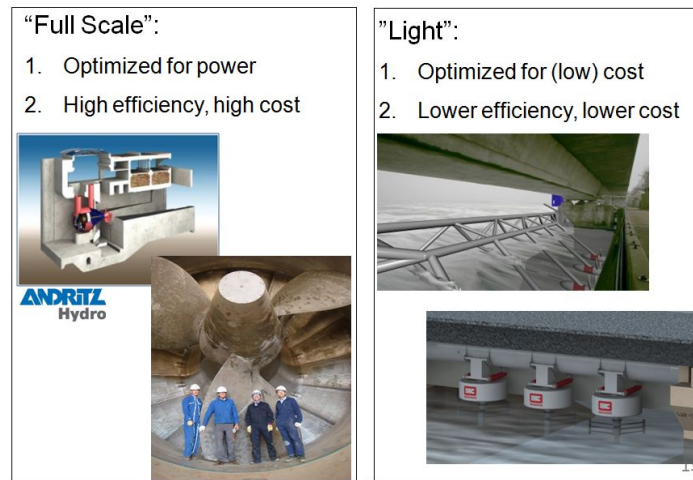


Figure 4.1 Two versions of Low head tidal power plants: "Full scale" and "Light", see Berkel (2014).

The two configurations reflect:

1. An integrated "Full Scale" tidal power plant, optimised for power production, in which the hydro-electric conversion technique is an integral part of the civil construction.
2. Add-on "Light" tidal power plant, optimised for low cost, in which the hydro-electric conversion technique is added to an existing or new built civil construction.

Depending on the project's characteristics: New built versus existing and Investment thresholds; either the "Full Scale" or "Light", or an intermediate version, may be appropriate.

### 5. CONCLUSION: MCA-RESULT: BEST AVAILABLE TECHNIQUE

The responses gave an arithmetic average score that, after rearrangement, is presented in a descending order. Here first the ranking will be displayed. Later the considerations will be given for the technique categories.

#### 5.1 Advice for "Full Scale" tidal and river hydropower plants

The ranking of the technique categories for the Full Scale and Light versions reads:

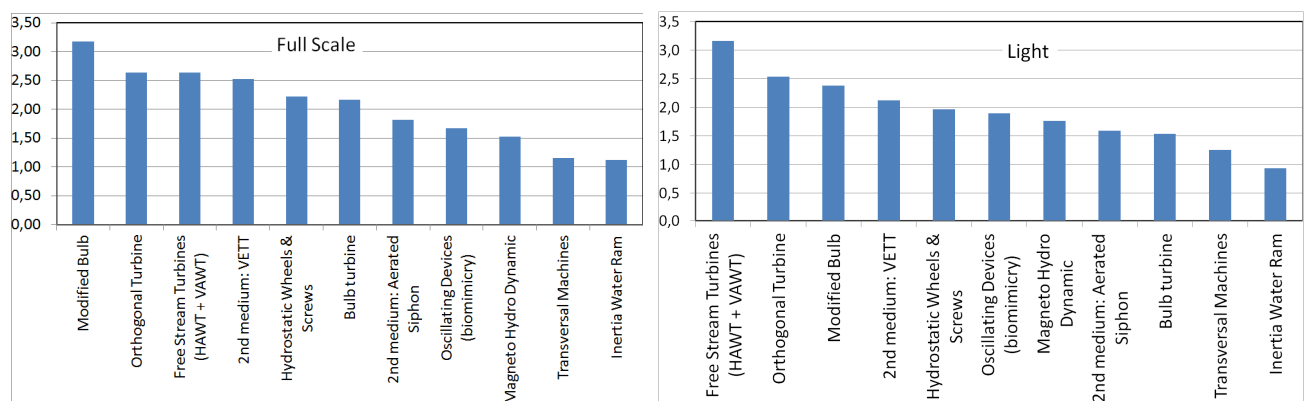


Figure 5.1. Ranking of the technique options for "Full Scale" and "Light" Tidal and River Hydropower plants.

As shown in figure 5.1 the modified bulb technology is identified as the Best Available Technique for Full Scale Ultra Low Head Tidal and River Hydropower Plants. The difference with no. 2: Orthogonal Turbines and no. 3: Free-Stream turbines is distinctive (0,5).

For the "Light" version, Free Stream turbines: **Horizontal Axis Water Turbine (HAWT)** or **Vertical Axis Water Turbine (VAWT)** is identified as the Best Available technique. Similarly as for the Full Scale version, the difference with no. 2: Orthogonal Turbines is distinct (0,5).



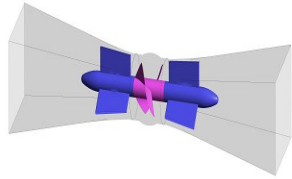
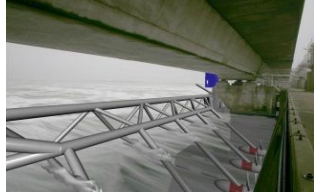
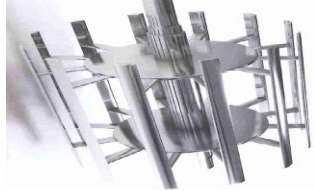
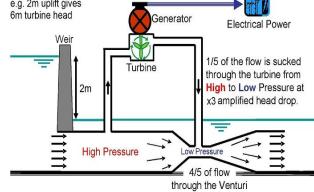
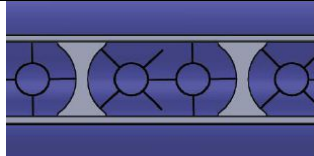
## 5.2 Discussion and evaluation

Regarding the ranking for the "Full Scale" and "Light" applications, the conclusions can be drawn:

- 1) The top-5 techniques in both applications cover the same categories, though not exactly on identical positions:
  - a) Modified bulb and Free Stream interchange positions # 1 and # 3 for the "Full Scale" and "Light" applications.
  - b) In both applications, Orthogonal Turbines are on position # 2
  - c) Likewise the Venturi Enhances Turbine Technique is on position # 4, and
  - d) Hydrostatic Wheels and Screws on position # 5.
- 2) Fish Friendliness (30 % weighting factor) has shown to be a critical success factor. On the basis of expert judgement, some techniques received a high rating on Fish Friendliness. If in further tests this would shown not to be true, these techniques would drop significantly in the rating.
- 3) "Technology Readiness" (25 % weighting factor) is found to be an important and somewhat strict criterion. Following the MCA-criteria as designed, techniques that are at this moment immature, consequently receive a low score. This however, does not take into account that after further development in the coming years, these techniques could become successful candidates.

It is encouraging to see that many alternatives rate better than the currently standard technique (bulb turbines); Recently developed modified bulb turbines are identified as the Best Available Technique for Full Scale version. Interesting are the runner-up positions: Orthogonal Turbines (#2), VETT (# 4) and Hydrostatic Wheels&Screws (#5).

Table 5.1. Best Available Techniques: Top 5 considerations

<p><b>Modified Bulb</b> If the claims and tentative test results regarding fish friendliness can be sustained, the modified bulb is evaluated as a strong candidate. Costs indications are low (~ 1000 Euro/kWe) and overall efficiency high (70 %). Several manufacturers market the modified bulb</p>	
<p><b>Free Stream Turbines</b> Free stream turbines provide a cost-effective solution for "Light" systems. Fish friendliness is proven for true free stream operation. Drawback is the low efficiency when operated in true free stream. "Light" versions are implemented in the Afsluitdijk and the Oosterschelde surge barrier.</p>	
<p><b>Orthogonal Turbines</b> This class of turbines has distinct advantages: Vertical axis with dry generator, simple layout and (claimed) low costs, reasonable efficiency and effectively fish friendly. The R&amp;D-advisory board would like to be convinced by further experimental evidence.</p>	
<p><b>Venturi Enhanced Turbine Technique</b> Performance and Fish Friendliness of VETT have been proven convincingly. If the claims regarding costs reduction can be sustained, VETT is identified as a strong candidate technique. The advisory board advices to further investigate the cost-reduction potential.</p>	
<p><b>Hydrostatic Wheels &amp; Screws</b> This category is interesting due to its potentially high conversion efficiency. Velocities are low which is advantageous for fish friendliness, but pose a drawback due to the large size and costs associated.</p>	

Following the identification of the Best Available Technique, Pro-Tide's R&D-advisory board proposed to actually test and demonstrate both the modified bulb and tidal stream (including orthogonal) techniques. The Venturi Enhanced Turbine Technique was selected for further desk-top research, to substantiate the claims regarding costs reduction.

## 6. FOLLOW-UP

In addition to ultra low head conversion techniques, at least two other topics play a major role in the viability of tidal power plants; namely costs for the civil construction and fish friendliness. Following Pro-Tide R&D board's advice, further efforts has been directed to these topics.

### 6.1 Costs reduction potential of civil works.

To further reduce costs for ultra low head tidal and river power plants, Pro-Tide has commissioned consultancy firm IV-Infra to explore the possibilities for costs reduction by:

- Smart phasing of construction sequences
- Innovative configurations
- Application of new materials

The project has been executed in close cooperation between IV-Infra, Pro-Tide team members and its R&D-board. In this project also a specific technique based on Venturi Enhanced Turbine Technique (VETT), marketed by VerdErg (UK), is further analysed.

Through a process of brainstorming, regular meetings and desk-top research, three alternatives for cost-reduction were devised: 1) Diffuser, housing highly efficient bulb turbines; 2) Ducted, straightforward "lego"-type constructions, housing ducted tidal stream turbines and 3) linear VETT, based on the venturi principle. The dimensions of the structures is derived from previous studies relating to the Brouwersdam project. Figure gives an impression of the structures.

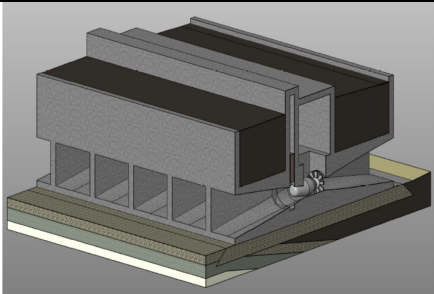
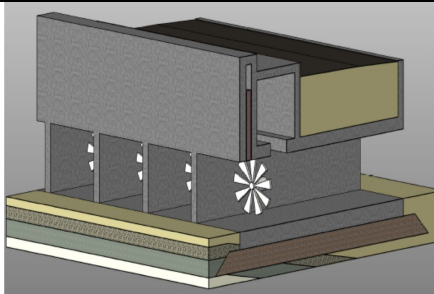
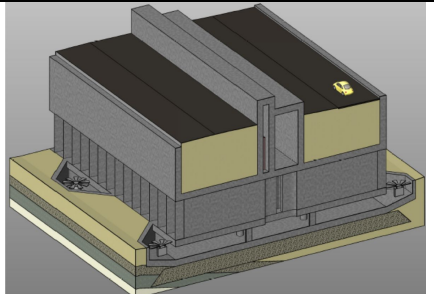
"Diffuser"	"Ducted"	"Linear VETT"
		
Construction method: "Wet" 662 m length, 35 m wide Capex: 318 M€ +/- 30 %, incl. VAT, excl Turbines	Construction method: "Wet" 135 m length, 30 m wide Capex: 75 M€ +/- 30 %, incl. VAT, excl Turbines	Construction method: "Wet" 200 m length, 35 m wide Capex: 138 M€ +/- 30 %, incl. VAT, excl Turbines

Figure 6.1. Civil construction options, evaluated for costs reduction potential, Spengen (2015).

Due to its geometrical straightforwardness with flat walls, the "Ducted" version in principle is most costs-effective. The flipside is that for a given power output, the turbine diameter must be larger than in case of the traditional diffuser configuration. The intriguing question whether increased turbine costs does not off-set the advantage of reduced civil costs, will be answered the coming months.

### 6.2 Guidelines for testing fish friendliness

In practice it is observed that turbine tests with life fish is executed frequently in a pragmatic and ad-hoc manner. Fish is introduced in the test set-up sometimes in a rough way, thereby biasing the final results as it is not clear to which extend fish is damaged by the turbine itself of the manipulation of fish in the test set-up. Furthermore a standard protocol is absent for handling and examination of fish prior and after the tests.

Given this state of affairs, Pro-Tide's R&D decided to initiate the set-up of guidelines for execution life fish tests. These guidelines are being derived by experts in the field of fish-ecology and turbine technology. The guidelines cover for example the design of the test set-up; handling procedures, species and length-class of fish and their origin (wild or farmed). In the process, consensus amongst the stakeholder groups (i.e. Ministry of Infrastructure and Environment, angler associations) is sought to arrive at a well-supported protocol, which will help further testing, and acceptance of the results.

### 6.3 Testing turbines for Fish Friendliness and Performance.

In May and June 2015 small scale turbines tests will be tested to demonstrate fish friendliness of tidal turbines. The tests will be done using a purpose built test-rig, shown in figure . The design follows the guidelines for life fish testing which are drawn-up within the framework of the Pro-Tide project (see 6.2). Tests are expectedly executed at the banks of the river NederRhine, close to the Nuon/Vattenfall hydropower plant at Maurik.

The test-rig consists of a ~12 m<sup>3</sup> high water tank and a ~12 m<sup>3</sup> low water tank with in between the turbine to be tested. Water passes the turbine due to the head difference between the two tanks. The high water tank is continuously fed with



fresh river water, while the low water tank discharges to the same river. Baffle plates in the tanks ensure even flow distribution at the turbine entrance and in the fish collection section in the tail tank. Life fish are introduced in the head tank, just before the turbine inlet section. After passage of the turbine, the life fish are collected in the low water tank, for further examination.

Given the turbine diameter of around 50 cm, tests will be done with small fish with maximum length of 20 cm. Given the Dutch setting regarding priority fish, test will involve the species Eel, Flounders, Salmon Smolts and Pikeperch. These species are carefully selected, also to represent the full scale target equivalents. Prior to the tests, the fish friendliness of the small scale and full scale turbines will be assessed using a dedicated fish damage model, which will be validated using the test results of the small scale tests.

In addition to the life fish tests, performance tests will be done to assess the power characteristics, especially of ducted tidal stream turbines. Where the performance characteristics of Free Stream turbines is known, this is not the case for their ducted versions, which are expected to be a cost effective option for low head tidal barrages. The aim of the test-rig is to unambiguously determine the power characteristics, under representative conditions: Close confinement, high blockage ratios and high speeds (typically 4 m/s).

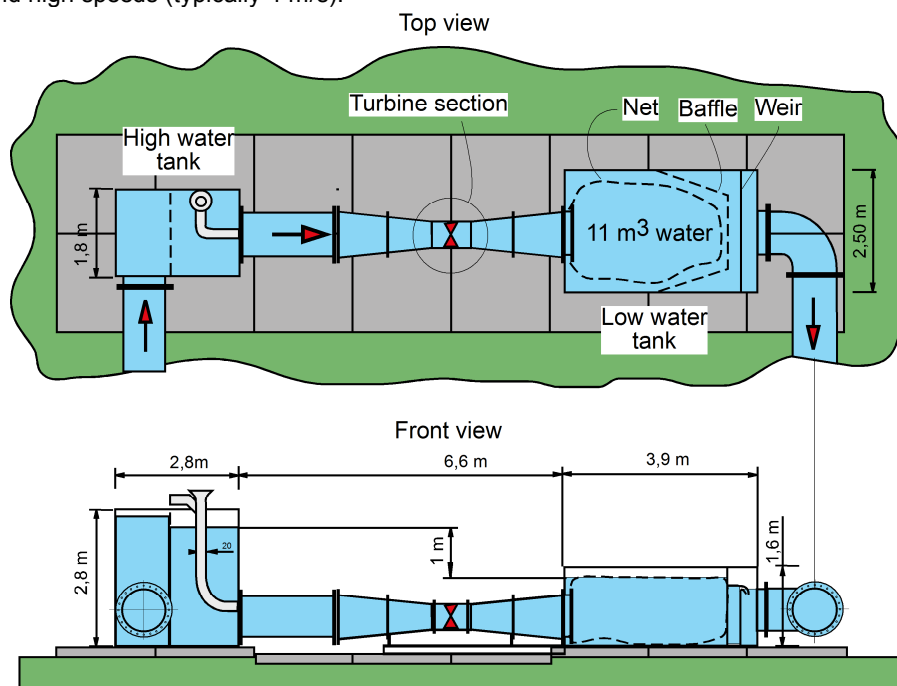


Figure 6.2. Pro-Tide-NL Test-rig for testing and demonstration of fish friendliness and performance of tidal turbines.

By virtue of the selection of the best available techniques, their impact on civil construction costs and their fish friendliness, Pro-Tide aims to contribute to the further Development, Testing and Promotion of Tidal Energy in coastal and estuarine zones.

#### ACKNOWLEDGMENTS

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