PRO-TIDE-NL
R&D-Board's advice

# Best Available Techniques for Ultra Low Head Tidal and River Hydropower

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Investing in Opportunities
This project has received European Regional Development Funding through INTERREG IV B.
INTERREG IVB

# Contents

# 1 PROLOGUE

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 $m^3/s$), 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 Technology, to further test and demonstrate this technology.

Crucial phase in the project is selection of the best available technology. This is done by the Pro-Tide-NL R&D-advisory board and, specifically for the ranking of technologies, 3 experts in the field.

As successful application of low head tidal hydropower relates to technical, economical and ecological viability, a Multi Criteria Analysis was used to identify the Best Available Technology. This report clarifies the process and content of the R&D-advice on Ultra Low Head Technology. Furthermore, an outlook is given about the next steps within the Dutch Pro-Tide project.



The R&D-advice would not have been possible without the input of many persons: Experts within market parties, public parties and research institutes. Many thanks is indebted to all involved in the quest for a financially viable and ecologically safe solution to harness ultra low head Tidal and River Hydropower.

On behalf of the R&D-advisory board,

J. van Berkel,
Chairman.

## 2 EXECUTIVE SUMMARY

On the basis of a Technology Inventory, condensed in Technology Factsheets, using the Multi Criteria Analysis, with the support from many experts, the Pro-Tide-NL-R&D-Advisory Board has identified the Best Available Technology For Ultra Low Head Tidal and River Hydropower generation.

In more detail, conclusions of the quest for the Best Available Technology may be summarised as:

1. In the inventory up to 10 independent technology categories are identified. Technology factsheets (comprising makes & manufacturers) are made, characterising the technology's key performance parameters.
2. An independent advisory board, with experts in the field of technology, ecology, morphology, economy and legislation is established. The advisory board was assisted by 3 external experts, giving input from science and market.
3. The Multi Criteria Analysis (MCA) technique is identified as a very useful technique to value multiple criteria and rank the options. The R&D-advisory board was unanimously in the selection of Best Available Technique. Ranking is done for a "Full Scale" Power plant (optimised for performance) and a "Light" version (optimised for investment costs).
4. In the MCA, electricity productions costs and Fish Friendliness are identified as the most important criteria, followed by Technology Readiness, Energy Yield and Exportability.
5. It is encouraging to see that many techniques rate better than the currently standard technique (bulb turbines); Recently developed modified bulb turbines are identified as the Best Available Technique (#1) for Full Scale version and (#3 for the Light version). Free Stream turbines are identified as the best candidate (#1) for the Light version and (#3) for the Full Scale version.
6. Interesting are the runner-up positions: Orthogonal Turbines (#2), Venturi Enhanced Turbine Technology (# 4) and Hydrostatic Wheels&Screws (#5).
7. The board suggests to promote further development by supporting:
   a. Laboratory Fish Friendliness tests of a Modified Bulb turbine.
   b. Performance test of a "reactive" Free Stream turbine.
   c. Initiate a costs-engineering study of an ejector-based technology.
8. The board recognizes that this MCA is a snapshot and technological development is ongoing. It is the board's opinion that above support from Pro-Tide will further stimulate the development of Ultra Low Head Tidal and River Hydropower.

# 3 INTRODUCTION

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

Previous studies (MIRT-project, Joule II) 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.

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 not very fish friendly. 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 Water Management (RWS) 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 report, 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. Organisation 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 report will follow the step-wise approach that was pursued in the identification of the Best Available technique:

Chapter 4 will address the search for new technology, synthesised in technique categories and documented in Technology Factsheets. Subsequently, in chapter 5, the MCA-analysis will be outlined. The organisation of the R&D-advisory board is given in chapter 6, and finally, in chapter 7, the board's advice is formulated, together with considerations.

# 4 SEARCHING & FINDING: TECHNOLOGY FACTSHEETS AND CATEGORIES

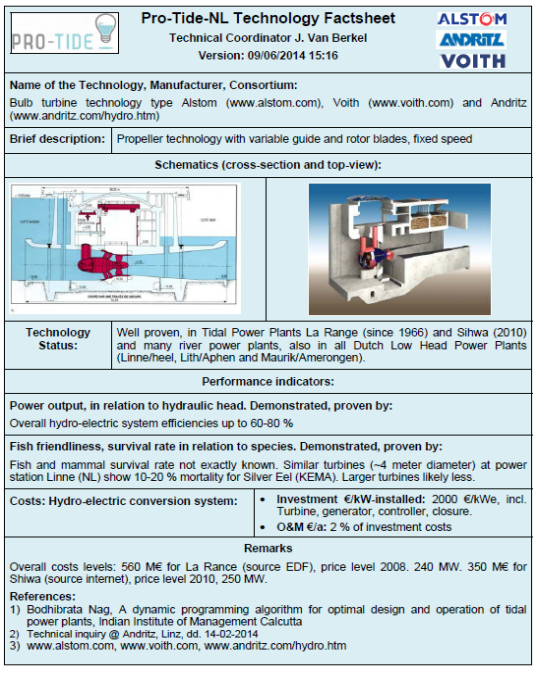
## 4.1 Inventory: Technology Factsheets

To facilitate the selection of the Best Available Techniques, a scan was made of unique techniques for conversion of 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[1] 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 (Van Berkel, 2013). The inventory is incorporated in the WP1's report on innovative technology (Goormans, 2013).

The results of the technology scan are reported in the form of Technology Fact-sheets, 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. An up-to-date set of the Technology Factsheets can be found in the appendix of this report. As an example, here the Technology Factsheet for the State of the Art Technology is given:





**Pro-Tide-NL Technology Factsheet**
Technical Coordinator J. Van Berkel
Version: 09/06/2014 15:16

ALSTOM ANDRITZ VOITH

**Name of the Technology, Manufacturer, Consortium:**
Bulb turbine technology type Alstom (www.alstom.com), Voith (www.voith.com) and Andritz (www.andritz.com/hydro.htm)

| **Brief description:** | Propeller technology with variable guide and rotor blades, fixed speed |
|---|---|

**Schematics (cross-section and top-view):**

| **Technology Status:** | Well proven, in Tidal Power Plants La Range (since 1966) and Sihwa (2010) and many river power plants, also in all Dutch Low Head Power Plants (Linne/heel, Lith/Aphen and Maurik/Amerongen). |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**
Overall hydro-electric system efficiencies up to 60-80 %

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**
Fish and mammal survival rate not exactly known. Similar turbines (~4 meter diameter) at power station Linne (NL) show 10-20 % mortality for Silver Eel (KEMA). Larger turbines likely less.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed:** 2000 €/kWe, incl. Turbine, generator, controller, closure.<br>• **O&M €/a:** 2 % of investment costs |
|---|---|

**Remarks**
Overall costs levels: 560 M€ for La Rance (source EDF), price level 2008. 240 MW. 350 M€ for Shiwa (source internet), price level 2010, 250 MW.

**References:**
1) Bodhibrata Nag, A dynamic programming algorithm for optimal design and operation of tidal power plants, Indian Institute of Management Calcutta
2) Technical inquiry @ Andritz, Linz, dd. 14-02-2014
3) www.alstom.com, www.voith.com, www.andritz.com/hydro.htm

*Figure 2.1 One of the 20 Technology Factsheets (example bulb turbines).*

[1] **W**aterwegen **en** **Z**eekanaal NV

## 4.2 Inventory: Category Overview

Figure 2.2 gives the category overview, which was distilled from the technology inventory, as represented in the Technology Factsheets.

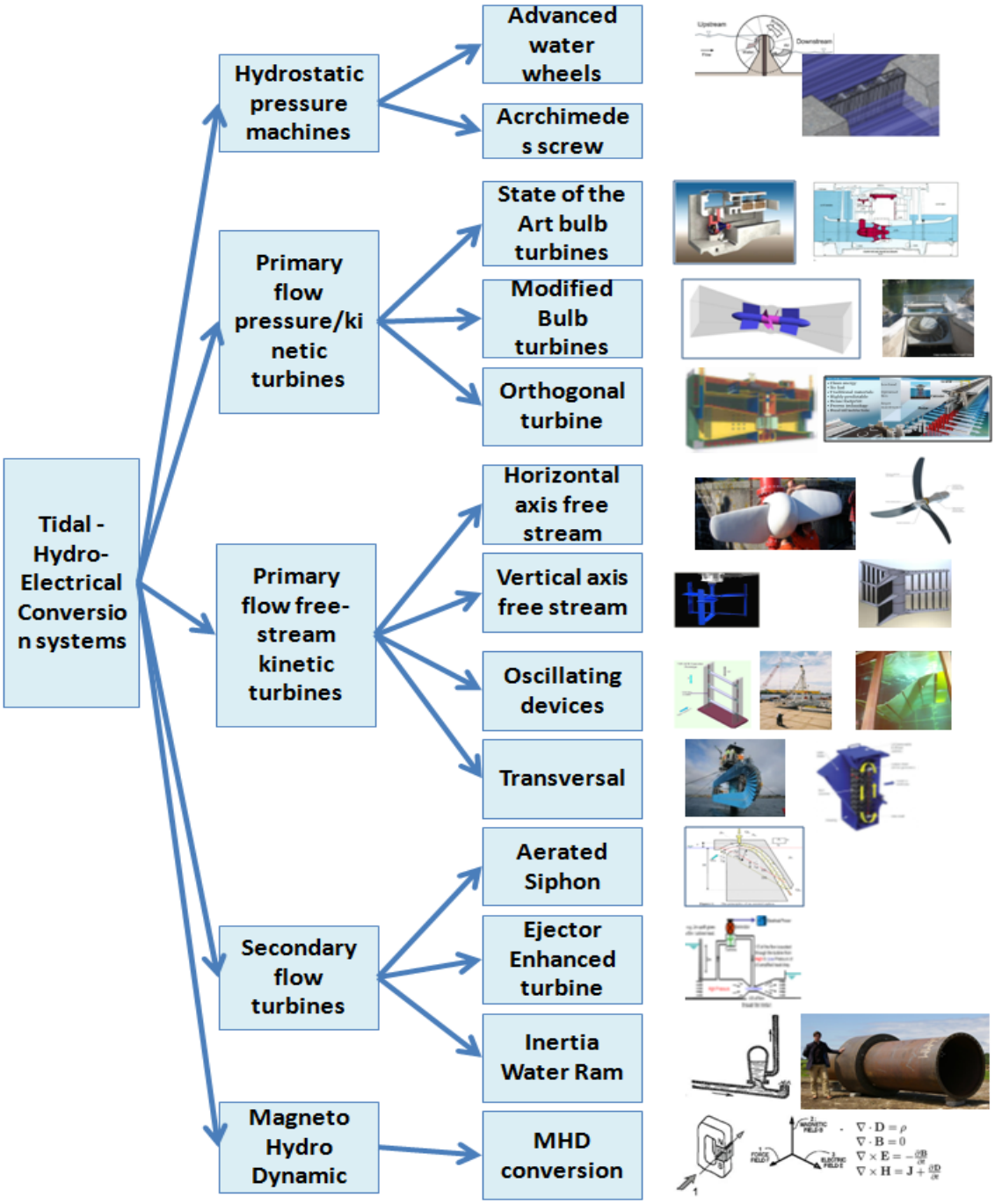



*Figure 2.2 Ultra Low Head technique's topology(categorization).*

It must be stated here that where the Technology factsheets give particular techniques (makes) and manufacturers, the category overview gives overarching categories (mostly non-manufacturer specific), that will be evaluated in the MCA-analysis.

# 5 MCA-ANALYSIS

## 5.1 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 WP1's Masterclass held in Antwerp, in May 2013 (Van Berkel, 2013), see table 5.1.

*Table 5.1 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 masterclass WP1 in Antwerp was invited to add criteria, of which both the Pro-Tide-NL Technical Coordinator, in cooperation with Pro-Tide-BE project leader and head of the Technological Research Group (Mr. R. Notele) made a further selection. The additions made during the masterclass were categorised and labelled according to the main important aspect. The tentative MCA-table was further evaluated by the Dutch R&D-advisory board, during its meeting on April 16, 2014. Partly bearing the Brouwersdam project in mind, the board modified the criteria and weighting according table 5.2.



*Table 5.2 Final list of criteria and weighting factors, May 2014*

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

Regarding the criteria, 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 (new developed) criterion 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 0-4.

**Technology Readiness (incl. Innovation)**

Technology Readiness Levels can be expressed in various ways, see e.g. http://en.wikipedia.org/wiki/Technology_readiness_level. As an example, here the TRL-scale of the US- Department of Energy (DoE) is adopted, modified to an MCA-score 0-4:

| MCA-score | |
|---|---|
| 0 | The basic components are integrated so it can be tested in a simulated environment. Examples include laboratory integration of components. |
| 1 | Model/prototype is tested in relevant environment: A laboratory or in a simulated operational environment. |
| 2 | Prototype near operational system. Represents a major step of an actual system prototype in an operational environment. |
| 3 | Technology is proven to work - Actual technology completed and qualified through test and demonstration. |
| 4 | 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[2] still is incorporated in the MCA via the kWh-costs and Energy Yield criteria.

## 5.2 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:

| Pro-Tide NL: Multi CriteriaAnalysis. 17-04-2014<br>Low Head HydroElectrical Conversion Techniques | | | | | Excellent | 4 |
|---|---|---|---|---|---|---|
| | | | | | 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% |
| **Modified Bulb** | | | | | | |
| **Orthogonal Turbine** | | | | | | |
| **Free Stream (HAWT + VAWT)** | | | | | | |
| **2nd medium: VETT** | | | | | | |
| **Hydrostatic Wheels & Screws** | | | | | | |
| **Bulb turbine** | | | | | | |
| **2nd medium: Aerated Siphon** | | | | | | |
| **Oscillating Devices** | | | | | | |
| **Magneto Hydro Dynamic** | | | | | | |
| **Transversal Machines** | | | | | | |
| **Inertia Water Ram** | | | | | | |

Above MCA table was used in the identification of the Best Available Technique by the R&D-advisory board and the external experts.

[2] Pumping in period with very low head across the dam, pays back multiple (2-3-times) in periods of higher heads.

### 5.3 Two Ratings

Rating for the Best Available technology is done for two configurations:

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.

Figure 6.1 gives two examples.

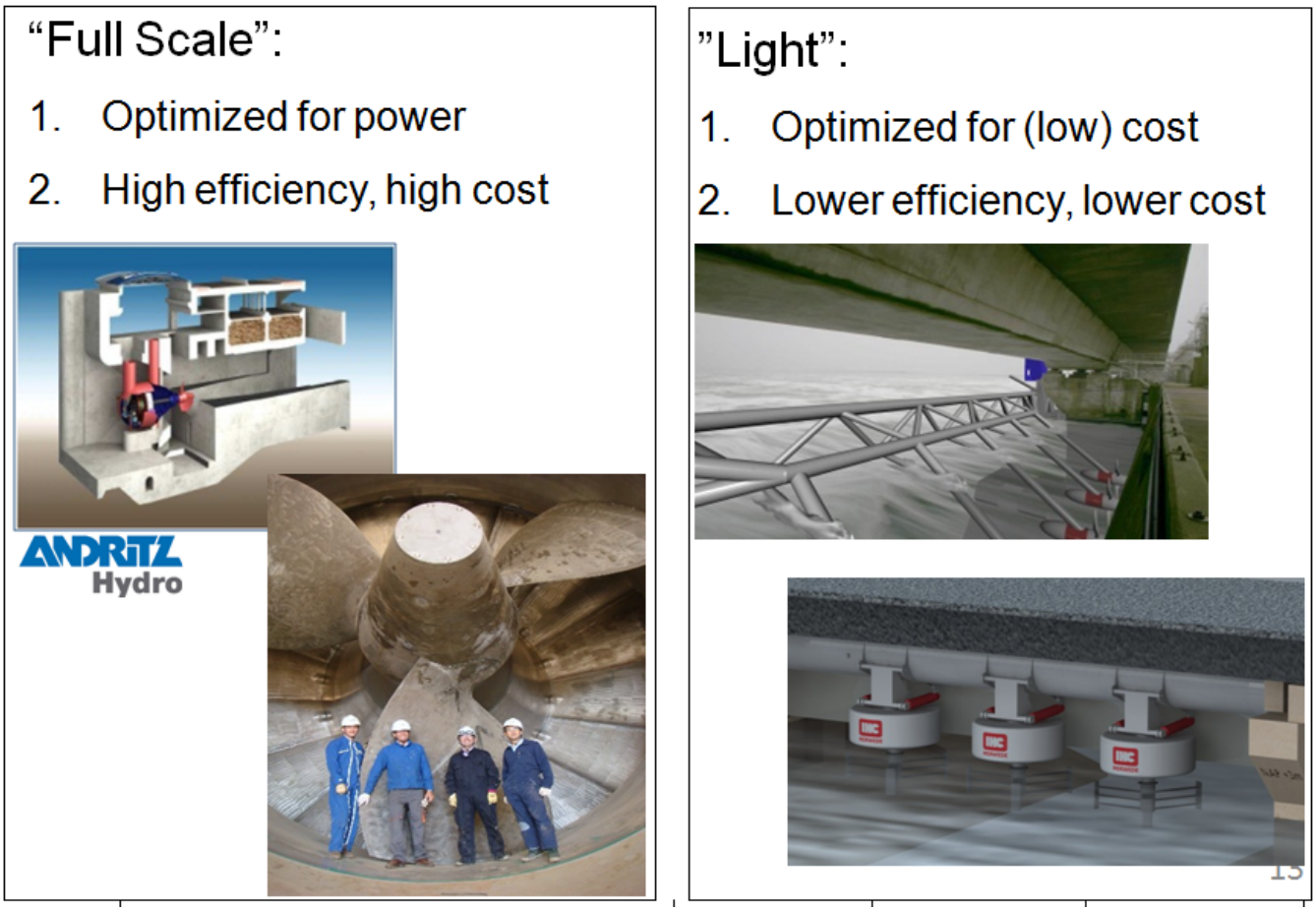



*Figure 5.1 Examples of an integrated (left) and add-on (right) Tidal power Plant.*

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.

# 6 ORGANISATION OF THE R&D-ADVISORY BOARD

## 6.1 Advisory Board Composition

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:

| | | |
|---|---|---|
| Mrs. Ilse Deurwaarder | Pro-Tide | Secretary |
| Mr. Jeroen Versteeg | PZE[3] | Legislation |
| Mr. Paul Paulus | RWS[4] | RWS Tidal Energy, Bekkencoordinator Grevelingen |
| Mr. André Breukelaar | RWS | Ecological aspects (Fish friendliness) |
| Mr. Marian Lazar | RWS | Morphological aspects |
| Mr. Menno Rikkers<br>Mr. Peter vd Does | RWS | Civil construction aspects<br>Installation aspects |
| Mr. Jacob van Berkel | Pro-Tide | Pro-Tide-NL Technical Coordinator, Chairman |

See figure 6.1 for a photograph of the board's members and consignee.



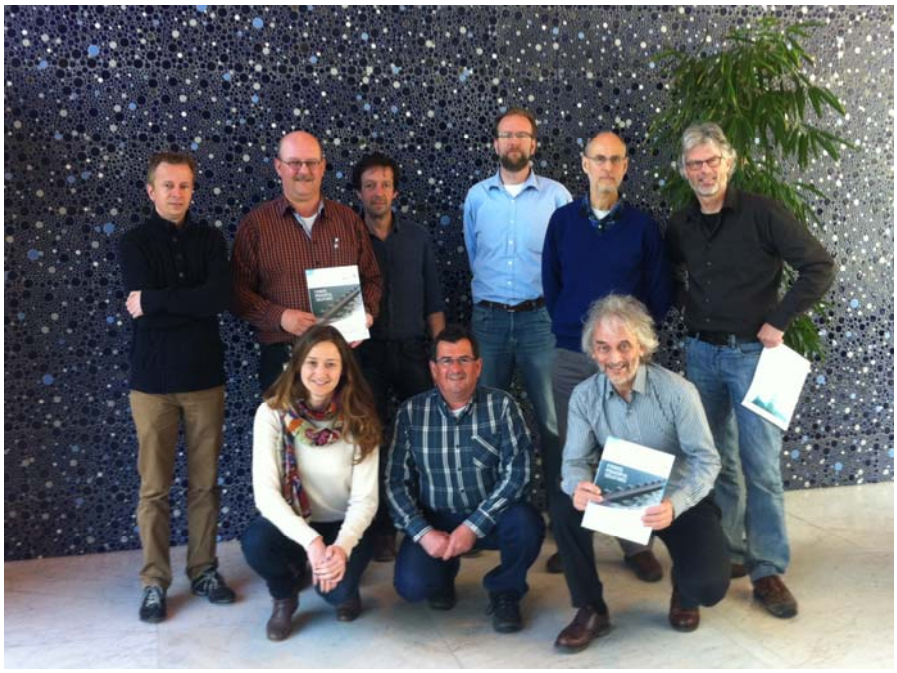


*Figure 6.1 Advisory Board: Top row, from left to right: J. Versteeg; L. vd Klip (consignor); A. Breukelaar; M. Rikkers; P. Vd Does and P. Paulus. Bottom row: I. Deurwaarder; M. Lazar and J. Van Berkel.*

[3] **P**rovince **Ze**eland

[4] **R**ijks**W**ater**S**taat: Agency of the Ministry of Infrastructure and Environment

All the advisory board members (excepts for the secretary) ranked the technology categories, outlined in figure 2.2, thereby using the MCA-table and procedure described in the previous chapter 5.

### 6.2 Advisory Board's Scope

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.

### 6.3 External experts

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 three external experts are:

| | | |
|---|---|---|
| Mr. H. Van Duivendijk | - | Former Delft University, Civil Engineering |
| Mr. T. Goormans | IMDC (BE) | Advisor WenZ (Pro-Tide partner) |
| Mr. P. Scheijgrond | MET-support | Secr. EWA, Marine Energy Consultant |



The input of the external experts was highly appreciated and incorporated in the selection procedure on an identical level as the opinion of the advisory board members.

### 6.4 Time-line and synopsis

The Advisory board had 3 meetings to arrive at a decision regarding the Best Available Technology:

| | |
|---|---|
| November 25, 2013 | Introduction, procedure |
| April 16, 2014 | Criteria and weighting factors |
| May 20, 2014 | Synopsis, formulation of R&D-advice |

This report is the cumulative result of the technology inventory condensed in the Technology factsheets, the category overview and the evaluation by the Advisory Board and external experts. The final concrete result is a ranking of the techniques, both for "Full Scale" and a "Light" Tidal or River Hydropower plant.

By using the MCA-method, synopsis 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, as will be presented in Chapter 7.

# 7 PRO-TIDE-NL R&D-BOARD'S EVALUATION OF THE BEST AVAILABLE TECHNIQUES

The responses gave an arithmetic average score that, after reshuffling, is presented in a descending order. In this chapter first the ranking will be displayed. Later, in chapter 7.3 the considerations will be given for the technique categories.

## 7.1 Advice for "Full Scale" Tidal and River Hydropower Plants

The ranking of the technique categories for the Full Scale version reads:

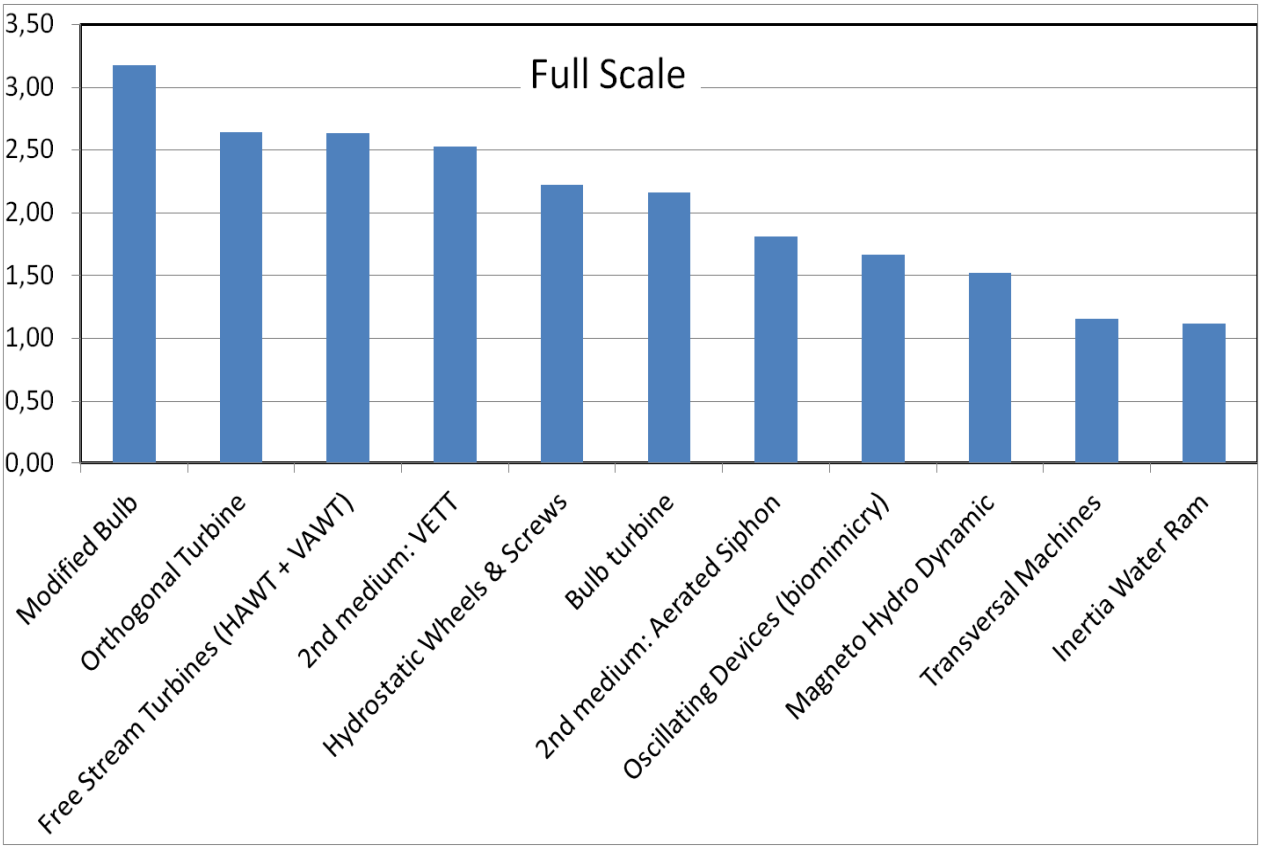



*Figure 7.1 Ranking of the technique options for Full Scale Tidal and River Hydropower plants.*

As shown in figure 7.1 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).

## 7.2 Advice for "Light" Tidal and River Hydropower Plants

An identical procedure as for the Full Scale Tidal and River Hydropower Plant was followed for the "Light" version, of which figure 7.2 gives the ranking.

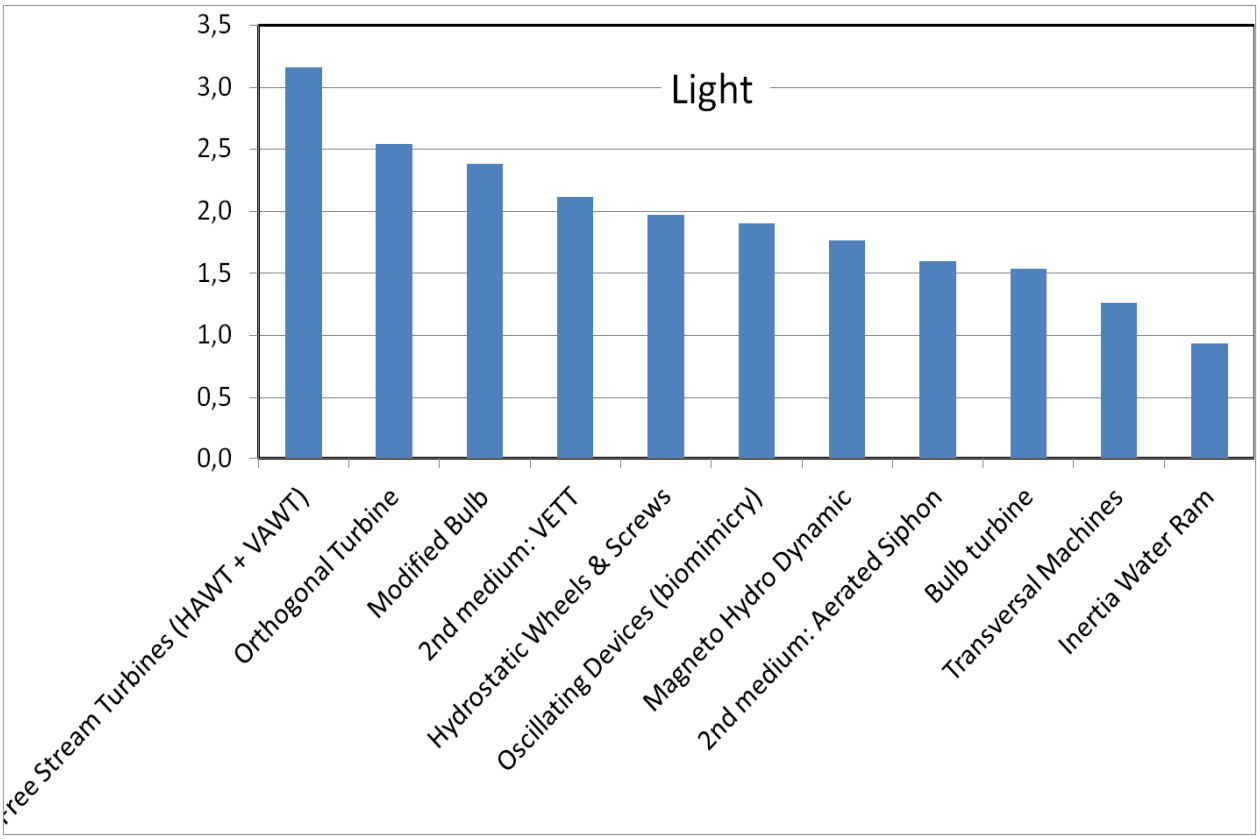



*Figure 7.2 Ranking of the technique options for "Light" Tidal and River Hydropower plants.*



For the "Light" version, Free Stream turbines: **H**orizontal **A**xis **W**ater **T**urbine (HAWT) or **V**ertical **A**xis **W**ater **T**urbine (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).

## 7.3 Discussion and evaluation

After analysis of the ranking for the "Full Scale" and "Light" applications, the conclusions can be drawn:

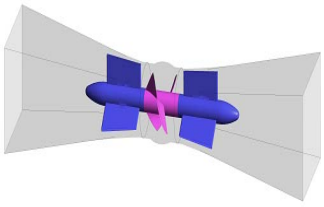
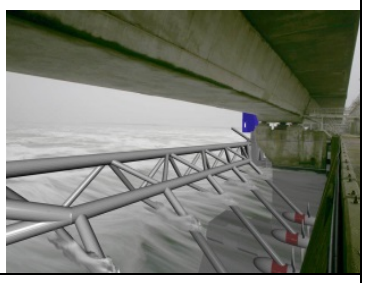
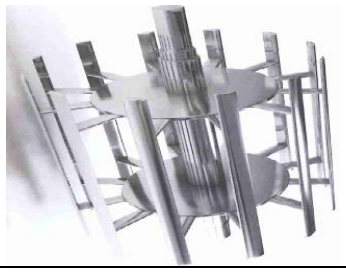
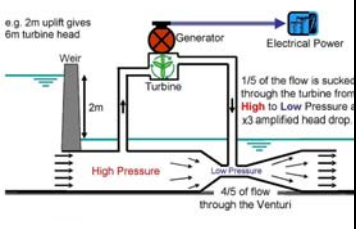
1) The top-5 techniques in both applications cover the same categories, though not exactly on identical positions:
   a) Modified bulb and Free Stream interchange positions # 1 and # 3 for the "Full Scale" and "Light" applications.
   b) In both applications, Orthogonal Turbines are on position # 2
   c) Likewise the Venturi Enhances Turbine Technique is on position # 4, and
   d) Hydrostatic Wheels and Screws on position # 5.

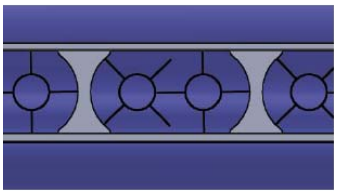
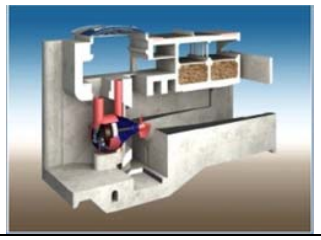
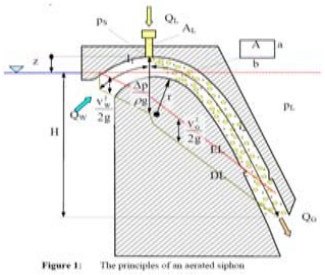
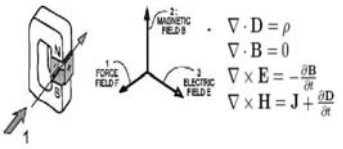
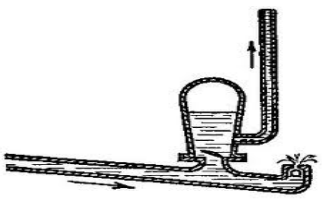
2) Fish Friendliness (30 % weighting factor) has shown to be a critical success factor. On the basis of expert judgement, some techniques received a high rating on Fish Friendliness. If in further tests this would shown not to be true, these techniques would drop significantly in the rating.

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).

**Technique category evaluation:**

| | |
|---|---|
| **Modified Bulb**<br>If the claims and tentative test results regarding fish friendliness can be sustained, the modified bulb is evaluated as a strong candidate. Costs are low (~ 1000 Euro/kWe) and overall efficiency high (70 %). Several manufacturers market the modified bulb |  |
| **Free Stream Turbines**<br>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. |  |
| **Orthogonal Turbines**<br>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 advisory board would like to be convinced by further experimental evidence. |  |
| **Venturi Enhanced Turbine Technique**<br>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. |  |

| | |
|---|---|
| **Hydrostatic Wheels & Screws**<br>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. |  |
| **Bulb technology**<br>The standard technology for conversion of low head tidal and river hydropower is rated in the lower half of the MCA-ranking. Though the technique is well proven, it is also a well known fish un-friendly and expensive technique. |  |
| **2nd Medium devices (Aerated Siphon)**<br>At the beginning of Pro-Tide project, the Aerated Siphon was identified as a strong candidate for the Best Available Technique. 2nd opinion research (Alidai, 2014) however showed that downsizing of the hydraulic head from the original 2- to 1 meter does have a strong adverse effect of efficiency (down to 6 %). For Low Head (>2 m) the technique still is attractive. |  |
| **Oscillating devices**<br>This class is inspired by movement of aquatic animals (fish, mammals). The slow moving oscillating technique is attractive because of it fish friendliness, but on the other hand is complex to effectively transform. Efficiency is expected not to be better than free stream turbine technique |  |
| **Magneto Hydro Dynamic conversion**<br>Fundamentally very attractive due to the absence of moving construction components. Given the current stage of (magnet) technology, costs are high. |  |
| **Transversal machines**<br>Regarding the transversal technique category, the advisory board's opinion is that the technique is likely to be as efficient as propeller techniques but at the same time more complex (vulnerable) and more expensive. |  |
| **Inertial Water Ram**<br>This category is based on the well proven technique to first increase hydraulic power density, before conversion into electrical energy. It has been suggested, but as far as known not applied. Efficiency and costs are reasonable. Due to pressure waves, fish friendliness is questionable. |  |

# 8 PRO-TIDE-NL R&D-BOARD'S EVALUATION OF THE BEST AVAILABLE TECHNIQUES

The advisory board advises to do further research on the top 4 techniques. With the support of Pro-Tide the advisory board hopes to further stimulate the development of the techniques and strengthen the whole sector.

## 8.1 Fish Friendliness Test of the Modified Bulb Turbine

As stated earlier Fish friendliness for the Modified Bulb turbines is of decisive importance. This category was rated high, also because of its fish friendliness that has been demonstrated.

Though in principle several candidate manufacturers exist: Nijhuis, VLH, Rolls Royce(?), the board suggest to proceed with Nijhuis as testing is most convincingly demonstrated for its fish friendly turbine. This turbine for application in river hydropower plants has movable guide vanes and fixed rotor blades. Tests have shown a high safety for Silver Eel, but to a lower extend for Trout. Regarding development of the tidal turbine, fish friendliness is expected to be better, as:



1) The tidal turbine does not have a wicket gate (only stay vanes).
2) Tests were done on scale (800 mm diameter), while full scale turbines would have a diameter of > 4 meter).

Figure 8.1 gives an impression if the fish friendly tidal turbine.

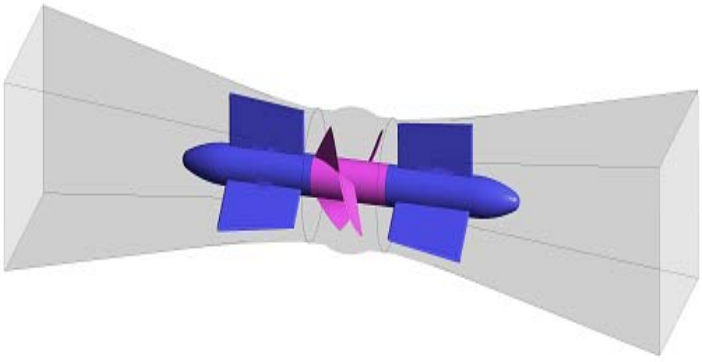


*Figure 8.1 Tidal turbine (without wicket gate)*

The board suggest to have the existing 500 mm scale model tidal turbine tested in the laboratory for fish friendliness. Research questions relate to: Fish friendliness (mortality rate) for Silver Eel and Trout, depending on head and flow rate. In the laboratory, tests can be done preferably with life fish.

At the same time, research should be focussed to development of a standard for fish friendliness testing.
It is the responsibility of the Pro-Tide-NL core-team to investigate the options, and in close cooperation with the manufacturer and the advisory board select the configuration (test-setup) for testing in semester 2, 2014 and semester 1, 2015.

## 8.2 Performance Test of "Reactive" Free Stream Turbines, incl Orthogonal

Given the high rankings of Free Stream turbines and Orthogonal turbines (and their physical similarities), the board proposes to combine the two categories in a new category termed "Reactive Free Stream Turbines".

The board indicates that pure Free Stream technology (free flow, without a civil construction) is not likely the Best Available technique for Low Head Tidal and River Hydropower generation, as in pure free stream configuration, the major part of the water flux flows around the turbine, without transferring a substantial part of its energy.

Better would be to -in more or less extend- focus the water volume flux to the propeller (as is done in any dam). The (ducted) turbine in that case will develop a higher resistance to the water flux and is therefore termed "reactive". "Reaction" in the technical sense is the fraction of the static water head that is subjected (taken up) by the hydro-electric conversion device itself. Low reaction turbines typically are free stream turbines, high reaction turbines are the Modified Bulb- and Kaplan turbines, which are primarily driven by pressure, rather than velocity of the water flow. Generally speaking it can be stated that the higher the reaction, the thicker (more solid) the blade.



A high reaction free stream configuration can be established by positioning the turbine in a duct, but also by positioning turbines closely together. The orthogonal turbine in that sense is a ducted Free Stream turbine.

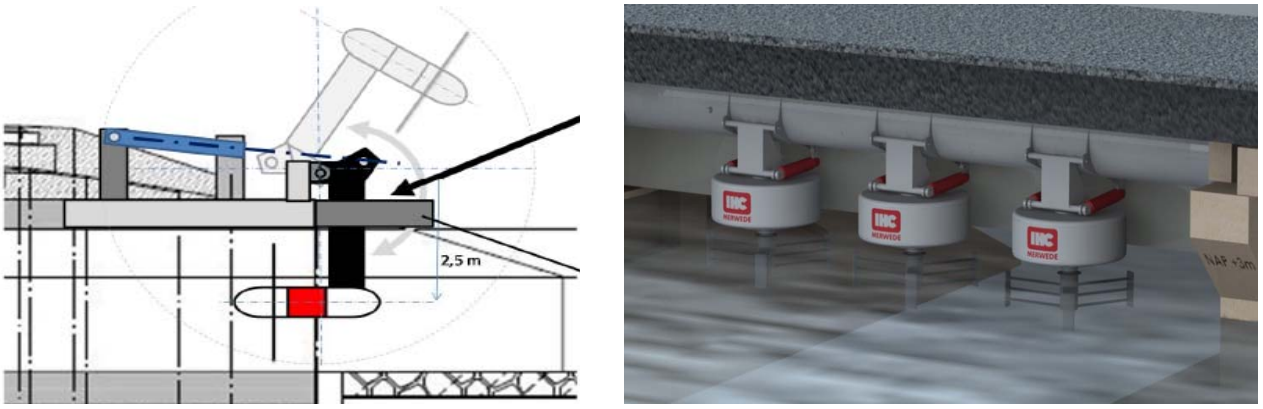



*Figure 8.2 Reactive (ducted) Free Stream Configuration, Left example project Waterdunen (Tocardo), Right Oosterschelde surge barrier (IHC)*

High reaction Free Stream is as yet not a standard technology. Manufacturers can design and build it, but tests are necessary to prove the performance (yield). Though performance in this respect is of prime importance, it must also be acknowledged that reactive free stream turbines not necessarily are as fish-friendly as the slim bladed free stream turbines.

The board suggest to organise a performance test of a high reaction free stream turbine in a laboratory duct. Research question would be the energy yield, depending on reaction (blockage, ducted), head and flow rate. For the manufacturers several options exists, to name: Tocardo; IHC, Schottel, Oryon, Rushydro, Blue Energy Canada. It is the responsibility of the Pro-Tide-NL core-team to investigate the options, and in close cooperation with the advisory board select the configuration (make, test facility) for testing in semester 2, 2014 and semester 1, 2015.

### 8.3 Costs engineering of VETT-technology

Venturi Enhanced Turbine Technology (VETT) is attractive because of (claimed) low costs and proven fish friendliness. In the SETT-project it was claimed that VETT: "Produces 2/3 of the power, against 1/2 of the costs".



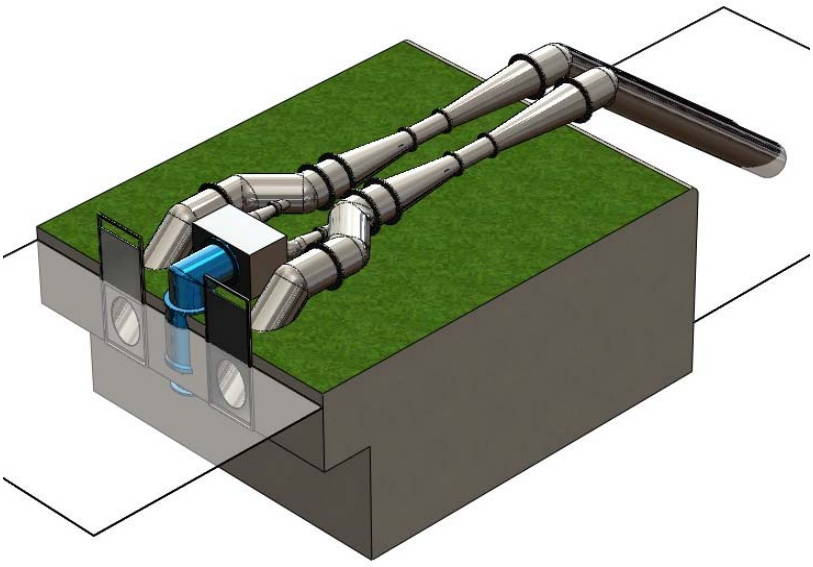


*Figure 8.3 Layout of VETT*

As performance and Fish Friendliness of VETT have been proven convincingly, the board proposes to support VETT with the facility of a cost-engineering study. This could be done by an independent party, in close cooperation with VerdErg, the owner and developer of VETT.

The board's proposal to the Pro-Tide team is to identify an independent cost-engineering firm that can further analyse the costs-advantage of VETT. The actual work can be done in the 2nd semester of 2014.

# 9 REFERENCE LIST


Alidai, A., Feasibility study of siphonic turbine , Deltares, February 2014

Van Berkel, J., Pro-Tide-NL Technology Factsheets, version 240314.

Van Berkel, J., Tidal Power Innovations, presentation given during Pro-Tide's Masterclass WP1, Antwerp, May 2013

Van Berkel, J., Waterdunen project, commissioned by Province of Zeeland, 2013.

Welsink, M. and Yazici, S., Innovatieve civiele technieken voor de Getijdecentrale Brouwersdam TUDelft, Civil Engineering, February 2014

Goormans, T., WP-1 report, November 2013.

# APPENDIX A: TECHNOLOGY FACTSHEETS

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

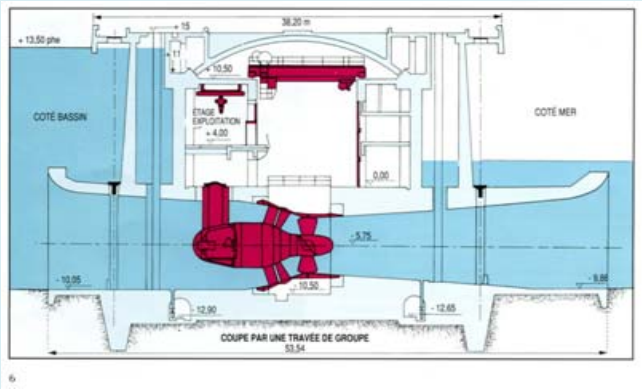
**Version: 07/07/2014 10:42**

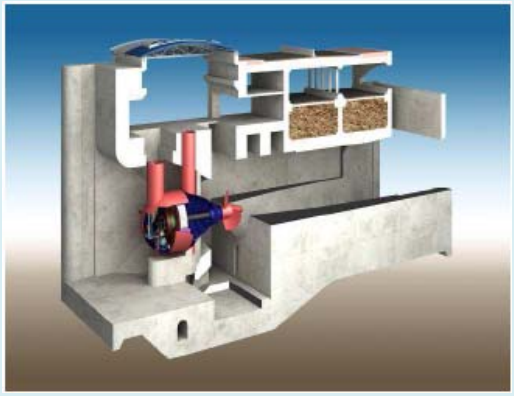
**Name of the Technology, Manufacturer, Consortium:**

Bulb turbine technology type Alstom (www.alstom.com), Voith (www.voith.com) and Andritz (www.andritz.com/hydro.htm)

| **Brief description:** | Propeller technology with variable guide and rotor blades, fixed speed |
|---|---|

**Schematics (cross-section and top-view):**



| **Technology Status:** | Well proven, in Tidal Power Plants La Range (since 1966) and Sihwa (2010) and many river power plants, also in all Dutch Low Head Power Plants (Linne/heel, Lith/Aphen and Maurik/Amerongen). |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Overall hydro-electric system efficiencies up to 60-80 %

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish and mammal survival rate not exactly known. Similar turbines (~4 meter diameter) at power station Linne (NL) show 10-20 % mortality for Silver Eel (KEMA). Larger turbines likely less.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed:** 2000 €/kWe, incl. Turbine, generator, controller, closure.<br>• **O&M €/a:** 2 % of investment costs |
|---|---|

**Remarks**

Overall costs levels: 560 M€ for La Rance (source EDF), price level 2008. 240 MW. 350 M€ for Shiwa (source internet), price level 2010, 250 MW.

**References:**

1) Bodhibrata Nag, A dynamic programming algorithm for optimal design and operation of tidal power plants, Indian Institute of Management Calcutta
2) Technical inquiry @ Andritz, Linz, dd. 14-02-2014
3) www.alstom.com, www.voith.com, www.andritz.com/hydro.htm

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

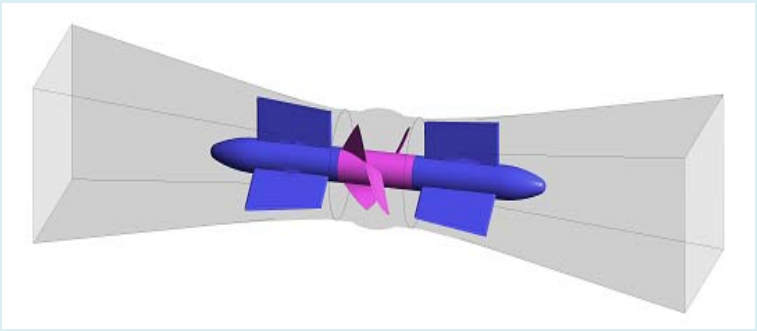
**Version: 07/07/2014 10:42**

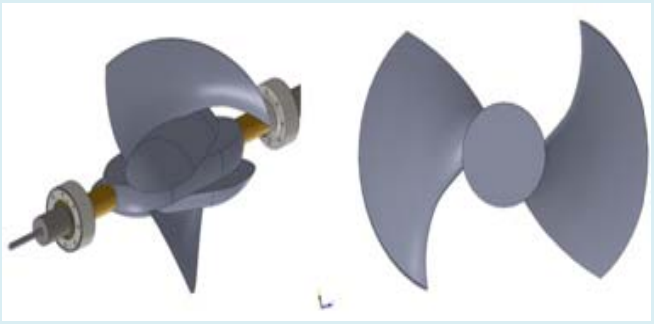
**Name of the Technology, Manufacturer, Consortium:**

Fish Friendly Turbine Pentair-Fairbanks-Nijhuis

| | |
|---|---|
| **Brief description:** | Bi-directional tidal fish friendly turbine with fixed stator vanes and ebb-flood switchable rotor blades. Direct drive generator with Permanent Magnets. |

**Schematics (cross-section and top-view):**





| | |
|---|---|
| **Technology Status:** | One-directional version for low head hydro tested on scale 1:5 (Ø 800 mm). Bi-directional tidal version (Ø 500 mm) is designed. Production underway, testing planned in March 2014. |

**Performance indicators:**

**Power output, in relation to hydraulic head.**

Measured turbine efficiency of (Ø 800 mm) version: 88 % @ 4 m head. CFD-based prognosis of full scale bi-directional version (Ø 5000 mm): 85 % @ 1 meter head. Overall hydro-electric system efficiency (including hydraulic conduit & electrical losses) in the range of 55-60 % @ 1 m head.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Tests with high speed (Ø 800 mm) one-directional scale version showed 100 % survival for Eels and ~95 % for shorter (20 cm) Trout representing juvenile Salmon. Cause (turbine or conduit) unknown. Survival rate for full scale low speed version most likely better. Final fish survival tests with one-directional scale version planned in March 2014 (Stieltjeskanaalsluis).

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 1000 €/kWe (econ.of.scale, low cost prod.)<br>• **O&M €/a:** 1 % of investment costs |

**Remarks**

Technology specifically developed for application in (Dynamic) Tidal Power Plants. Possibly up-scaled test version will be tested in Grevelingen Tidal Testing Centre and/or a Dutch River Power Plant. The full scale tested version will be available on demand.

**References:**


1) Technical inquiry @ Nijhuis, Winterswijk, dd. 23-01-2014
2) Confidential reports.
3) www.fairbanksnijhuis.com

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Aerated Siphon, Lancaster University

| | |
|---|---|
| **Brief description:** | Aerated siphon, using air as a second medium to drive low cost high rpm gas turbines, no moving components in primary water flow and therefore supposedly fish-friendly. |

**Schematics (cross-section and top-view):**

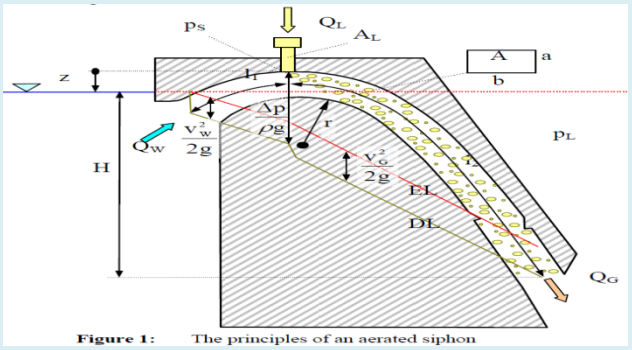



**Figure 1:** The principles of an aerated siphon

| | |
|---|---|
| **Technology Status:** | Extensively tested in the laboratory of Lancaster University, with a head of 2 meters, and on pilot scale in low head rivers. Overall efficiency ~50 % claimed Independent (tentative) check by Deltares gives a (much) lower indication of ~ 6%. |

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Overall hydro-pneumatic efficiency of 50 % anticipated by Lancaster for a head of 2 meter and conduit diameter of 200 mm. Deltares gives a 7% efficiency for a head of 1 meter.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Though expected, fish friendliness is not yet proven. Tests for similar air-lift pumps (Vopo-pump) have shown fish-friendly characteristics (ref T. Vrieze, Atkb)

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 500 €/kWe (gas turbine)<br>• **O&M €/a:** 1 % of investment costs |

**Remarks**

**References:**


1. Mardiani-Euers, E., A Study of Low head Hydropower using a siphon system and conversion to air pressure, PhD-Thesis Lancaster University
2. Alidai, A., Feasibility study of siphonic turbine, Deltares, 2014

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

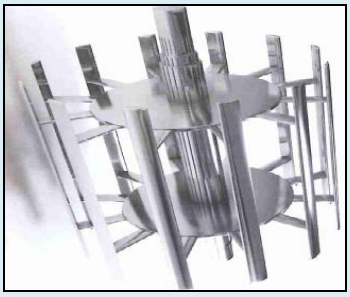
**Version: 07/07/2014 10:42**

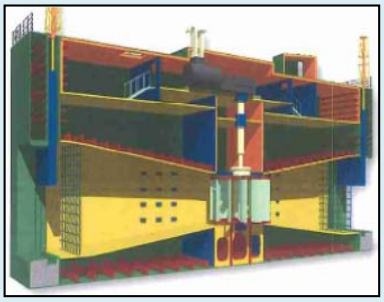
**Name of the Technology, Manufacturer, Consortium:**

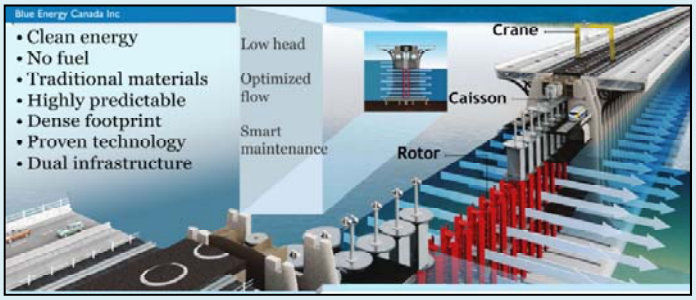
Orthogonal Turbine Technology, JcNiies (Rushydro) and BlueEnergy (Davis turbine)

| **Brief description:** | Vertical axis bi-directional tidal turbine with fixed rotor blades (cross-flow rotor). |
|---|---|

**Schematics (cross-section and top-view):**








| **Technology Status:** | Tested on 2,5- HAWT and 5 meter diameter VAWT by Rush Hydro in Kislaya Guba since 2007 (after refurbishment of the old (1966) Kaplan turbine). |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Overall hydro-electric system efficiency of up to 70 % (RusHydro), Blue Energy's Tidal Bridge lists 45 % (c.f. website)

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

No tests done yet, 200 mm screen mounted (OT), model predicts 100 % fish friendliness for fish < 300 mm length.

**Costs:**

Rushydro states that due to simpler layout and shape (1D blade curvature), costs are 20-30 % lower than for a comparable bulb turbine. 800 €/kW (for a 2.5 MW, 5 meter diameter OT, see email.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 800 €/kWe<br>• **O&M €/a:** estimated 1 % of investment costs |
|---|---|

**Remarks**

Mentioned as an interesting candidate in the Severn Estuary project.

**References:**


1) Shpolyanski, Yu., B., The New Orthogonal Turbine for Tidal, Wave and Low Head HydroPower Plants, JsC Niies, Russia
2) http://www.bluenergy.com/technology_method_tidal_bridge.html
3) Email Mr. Sobolev, February 26, 2014

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

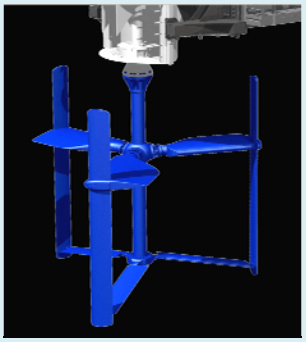
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Free-Stream Turbines (VAWT), combined Darrieus and Wells, IHC-Merwede

| | |
|---|---|
| **Brief description:** | Omni-directional tidal turbine with fixed blades, Direct Drive (E-excited) generator up to 1 MW |

**Schematics:**



| | |
|---|---|
| **Technology Status:** | Ocean Mill technology tested in C-energy project at jetty Borssele (Zeeland refineries). Up-scaled turbines (diameter x height = 7 x 7 m, 1 MW) in preparation for application in Easterscheldt Barrier. Basic design done, installation foreseen in 2015 |

**Performance indicators**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Current rotor efficiency Cp ~ 0,35. Overall efficiency (based on total throughput, with 50 % rotor coverage OSK) estimated at 16 %. For Brouwersdam with 66 % rotor blockage and (through higher reaction) increased Cp, overall efficiency could increase significantly. New rotor design necessary, to be proven & demonstrated. ANSYS CFD investigation underway.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Turbines are not tested for fish survival rate. Fish mortality is not reported (not anticipated, given the low speed (20-25 RPM) and tip speed ratio of 2,1). Ecological impact of similar turbines (MCT @ Stanford Loch) showed to be undetectable.

**Costs: Hydro-electric conversion system current 7 x 7 $m^2$ design:**

- **Investment €/kW-installed (prognosis):** 1500,- €/kW, (for 1st series of 10-15 pcs), incl. support frame.
- **O&M €/a:** 2 % of investment costs (OSK), 1,5 % foreseen for Brouwersdam

**Remarks**

**References:**


1) Technical inquiry @ IHC Alblasserdam, dd. 28-01-2014

2) www.ihctidalenergy.com

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

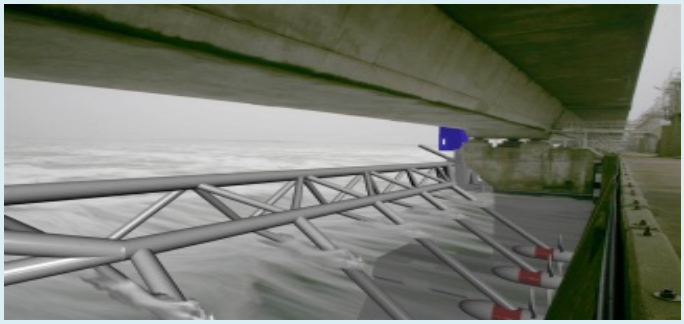
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

In-shore Tidal Turbines (HAWT), developed and marketed by Tocardo

| | |
|---|---|
| **Brief description:** | Bi-directional tidal turbine. Direct drive generator with Permanent Magnets with reverse, non-pitch rotor for use in bidirectional currents. |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Tests started in Den Oever in 2005. In 2014 Den Oever will be expanded and also planned is the installation of five T200 turbines in the Oosterschelde storm barrier. Furthermore Tocardo is in the implementation phase of installing four T100 turbines on a floating platform in a fast flowing Himalaya river in Nepal. Tocardo is involved in project Waterdunen. |

**Performance indicators**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Standard free flow rotor efficiency Cp ~ 0,4. For the standard turbine placed in a 100 % confined (duct) flow a theoretical efficiency is claimed at 67 %. Roughly this would imply 23 kW/m$^2$ rotor area at 1 meter head.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

For a free stream turbine, fish monitoring tests were conducted in 2006 in Den Oever. No evidence was found that the fish were injured by the turbine.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 1250 €/kW (@ 1 meter head) excluding foundation, installation and other project costs<br>• **O&M €/a:** 20 – 50 euro/MWh per year (3 - 8 % of investment costs) |

**Remarks**

**References:**


1) Technical inquiry Tocardo

2) Confidential reports

# Pro-Tide-NL Technology Factsheet

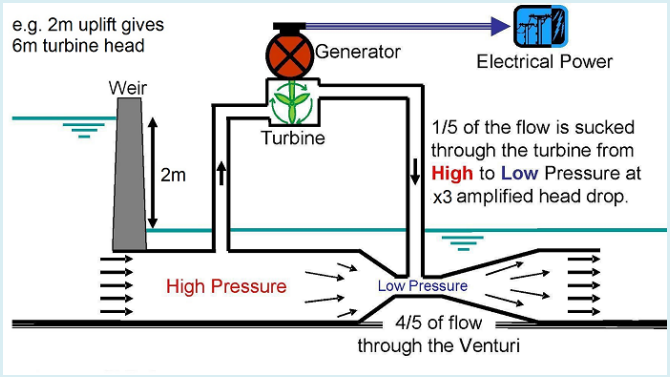
**Technical Coordinator J. Van Berkel**

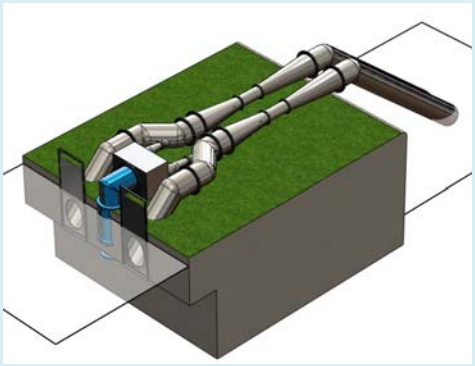
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**
Venturi-Enhanced Turbine Technology ('VETT'), VerdErg Renewable Energy Ltd, UK

| | |
|---|---|
| **Brief description:** | Increasing the turbine head in a secondary flow induced by pressure depression in the venturi (throat). Power extracted by the water turbine in the secondary flow claimed at a ~ 3 fold pressure head and a 20% flow rate. Costs advantage by simpler civil construction and less expensive turbines. Claimed is "two-thirds of the power at half the costs," when compared with a traditional barrier system. |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Two configurations: 1) Linear and 2) Co-axial VETT. In development by VerdErg and tested at BHR Group Cranfield (UK). Technology into the SETS Severn Estuary Embryonic Technology scheme. Co-axial VETT most advanced, TRL-level 5-6. |

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Field and Laboratory performance certified by Lloyds Register demonstrating 43% hydraulic conversion efficiency on superseded design in 2012. Coaxial configuration reached 50% in 2013 with 55%-60% anticipated.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish-friendly tests done at Vis Advies (NL) with linear VETT, zero fish damage observed.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed**: 3500-6000 €/kWe for a 30 MW system for Brouwersdam, incl. venturi assembly, turbine/generator, power management system, excl. civil works). Civil cost are minimised if siphonic configuration is suitable on the existing barrier<br>• **O&M €/a**: anticipated <1 % of investment costs |

**Remarks**

**References:**


1. Demo-visit in February 20, Cranfield (UK), Technical inquiry.
2. Confidential reports.
3. Bruijn. Q.A.A. de., H. Vis, & J.H. Kemper, "Test on fish survivability of the Venturi Enhanced Turbine Technology" Report: VA2012_33, 2013

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

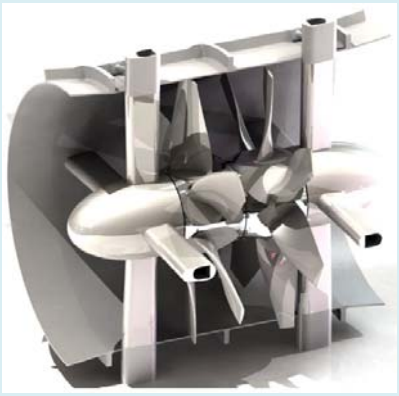
**Version: 07/07/2014 10:42**

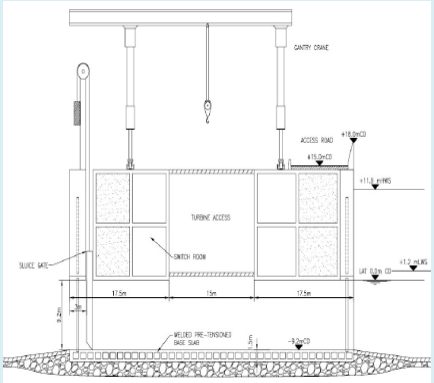
**Name of the Technology, Manufacturer, Consortium:**

Rolls Royce and Atkins

| | |
|---|---|
| **Brief description:** | Concept of a dual generation axial turbine "Blue" design for Ultra Low Head Scheme Severn Estuary. |

**Schematics (cross-section and top-view):**






| | |
|---|---|
| **Technology Status:** | Within the Severn Embryonic Technology Scheme (SETS) Rolls Royce designed two turbines both without diffusers: "Blue": A fixed RPM, variable pitch axial turbine with two counter rotating rotor's and "Red": a variable RPM single rotor machine that can be pivoted towards incoming tide. Due to technical reasons (Variable RPM, rotating equipment, fish mortality) "Red" is suspended. Concept "Blue" was later adopted by Hafren consortium. No prototype has been build so far. |

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Turbine efficiency is claimed at more than 90 % over the majority of the operating conditions (2-3 m head for the Severn).

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Claimed is a fish friendly design, due to tip low speeds (<9 m/s). No tests done.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed:** The expected normalised installed cost of the turbine is 850 £/kWe.<br>• **O&M €/a:** estimated @ 1 % of investment costs |

**Remarks**

**References:**


1) Atkins and Rolls Royce, Concept Design of a Very Low Head Dual Generation Tidal Scheme for the Severn Estuary, Volume 1: Summary Report DNS 159636 Issue 1, February 2010

2) House of Commons, Energy and Climate Change Committee, A Severn Barrage? Second Report of Session 2013–14, *Volume I*

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

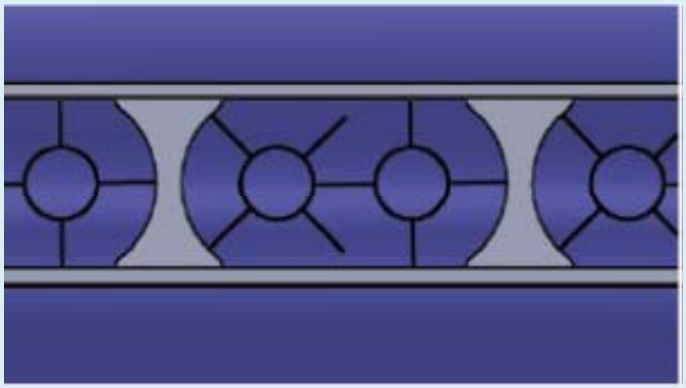
**Version: 07/07/2014 10:42**

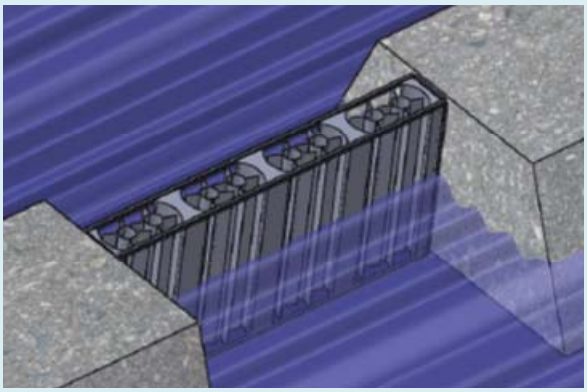
**Name of the Technology, Manufacturer, Consortium:**

RONAMIC Rotary Equipment, Noordwijk (NL)

| | |
|---|---|
| **Brief description:** | Positive displacement technique, based on counter rotating rotors. |

**Schematics (cross-section and top-view):**





| | |
|---|---|
| **Technology Status:** | Based on patent US2335817A (1), preliminary tests are done with a first prototype. |

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Anticipated max. efficiency 40-50 %, ~ 100 kW for a rotor-set of 5 m long, 1,7 meter width, @ 1 meter head and 2,5 m/s.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish-friendly testing is not performed yet.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** in Delta-layout 3000 €/kWe.<br>• **O&M €/a:** estimated at 1 % of investment costs |

**Remarks**

**References:**


1) www.ronamic.com

2) US2335817A (1)

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

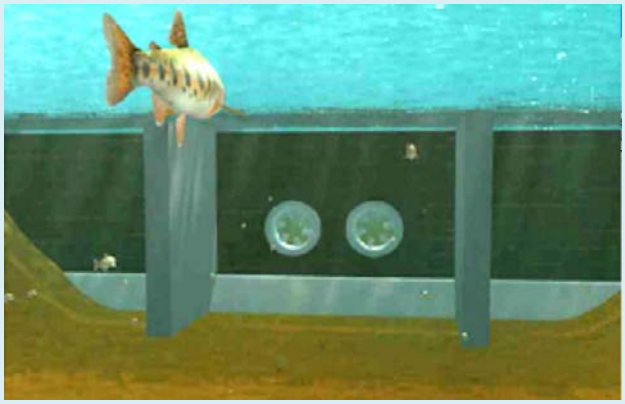
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

CCM (Owner of Hydroring)

| | |
|---|---|
| **Brief description:** | Small open hub turbine, in fish friendly version 80 kW and full power 100 kW. After failure of company Hydroring, the technology is owned by CCM Nuenen.<br>Especially suited for easy integration in sluices and weirs |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Full scale version build and tested on a barge in Dordrecht (October 2012) |

**Performance indicators:**

**Power output, in relation to hydraulic head. Demonstrated, proven by:**

Measured overall efficiency at a head of 3,25 m and 4,4 $m^3$/ flow rate is 30 %.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish-friendliness is claimed, due to the open hub. Testing is not performed yet.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** No information given.<br>• **O&M €/a:** estimated at 1 % of investment costs |

**Remarks**

**References:**


1) Demonstration October12, 2012

2) Confidential report CCM

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

**Version: 07/07/2014 10:42**

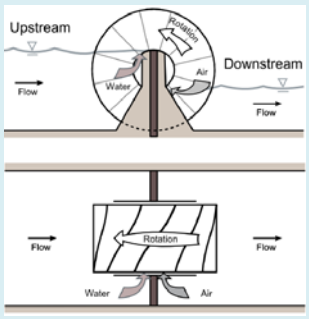
**Name of the Technology, Manufacturer, Consortium:**

Positive Displacement Technology: Stau Druck Machine, Rotary Hydraulic Pressure Machine (also representing Archimedes Screw), utilizing hydrostatic pressure, rather than velocity

| **Brief description:** | Improved version of Water Wheels, modified for high efficiency & high flow rate |
|---|---|

**Schematics (cross-section and top-view):**

The *Staudruckmaschine*, SDM (Brinnich, 2001)




| **Technology Status:** | Tested in laboratory and on pilot scale, for one-directional low head hydro applications. Developed from the classical water wheel technology by Brinnich (Austria), Aqualienne (FR) and Soton (Southampton) which we will visit in May 2014! |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Overall hydro-electric system efficiency tested at 80 % (peak). Flow capacity 1,3 $m^2/s$ @ 1 meter head.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish-friendly tests done. Reports available, data to be analysed.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 3000 €/kWe (current figure)<br>• **O&M €/a:** ... % of investment costs |
|---|---|

**Remarks**

**References:**


1) Senior, J., P. Wiemann and G. Muller, The Rotary Hydraulic Pressure Machine, University of Southampton.

2) Brinnich, Wicon, Austria

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

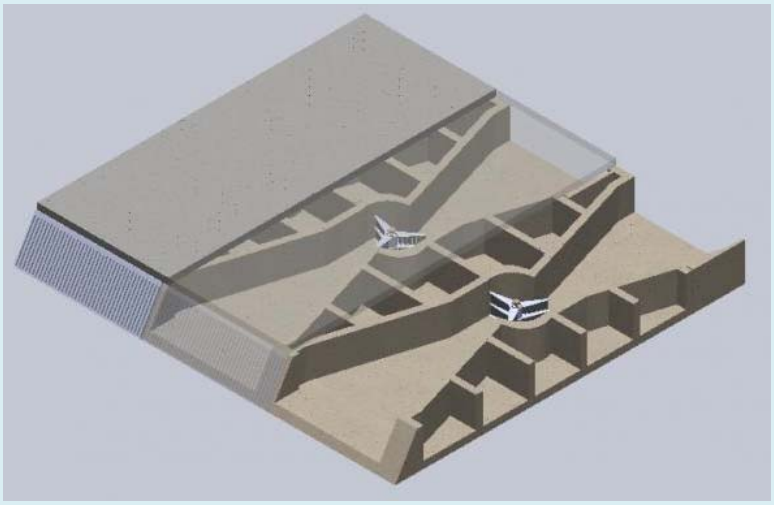
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Oryon Watermill, Deepwater Energy

| | |
|---|---|
| **Brief description:** | Drag VAWT machine, based on flapping louvres, similar to Worms Waterwheel (HAWT). |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Tested on scale @ Deltares and on full scale for fish friendliness as a free stream device in river the Rhine, 2013 and for larger heads (1 meter) tested at Ulft. |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Overall hydraulic efficiency (verified by KEMA) assessed at 38-39 % (Rhine tests). Tip speed ratio ~ 1. Small systems require a speed up transmission i.e. 1:10 for system in Ulft. Above 250 kW a direct drive submersed generator.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Tested for fish friendliness in the Rhine (Imares). No fish damage reported.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 2750 €/kWe incl housing, turbine-generator, control unit<br>• **O&M €/a:** ... % of investment costs |

**Remarks**

**References:**


1. Witnessed fish friendliness (Rhine) test 05 November 2013
2. Technical Inquiry March 19, 2014
3. Witnessed test (Ulft) 05 March 2014
4. Confidential reports.

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

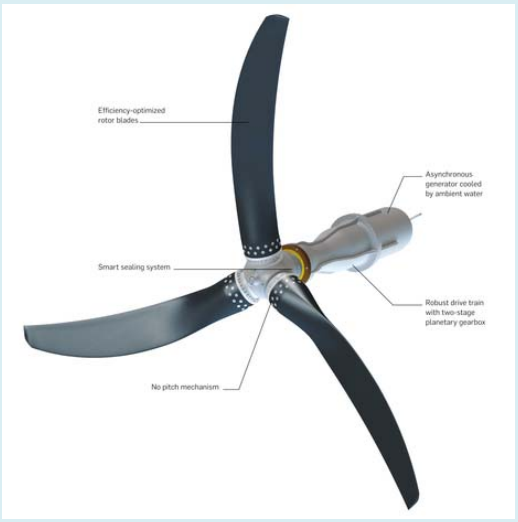
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Tidal turbine, Schottel

| | |
|---|---|
| **Brief description:** | HAWT free stream turbine, geared, asynchronous generator |

**Schematics (cross-section and top-view):**




| | |
|---|---|
| **Technology Status:** | Tested on full scale 4 meter diameter, 50 kW @ 2,7 m/s with a tug boat |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Expected rotor efficiency Cp ~ 0,45 For Brouwersdam with Ø 4 m rotor, placed in 5 x 15 conduit.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Turbines are not yet tested for fish survival rate. Fish mortality is not anticipated, given the low speed (60 RPM) and tip speed ratio of 4,5.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 2000 €/kWe (scale of economy: 20 machines, excl support structure, excl. transformers)<br>• **O&M €/a:** ... % of investment costs |

**Remarks**

**References:**


1. Technical inquiry @ Schottel, Spay (DE), March 7, 2014
2. Confidential reports.

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

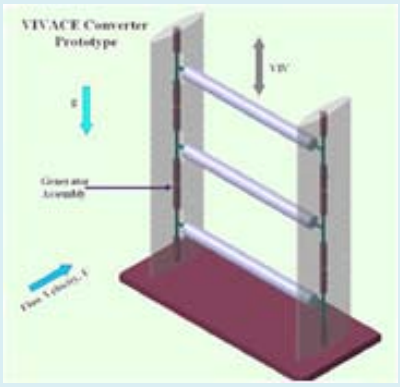
**Version: 07/07/2014 10:42**

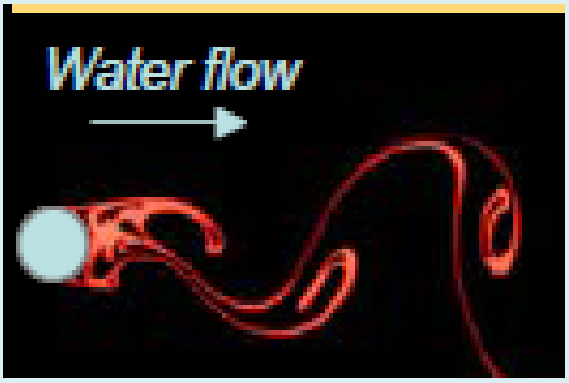
**Name of the Technology, Manufacturer, Consortium:**

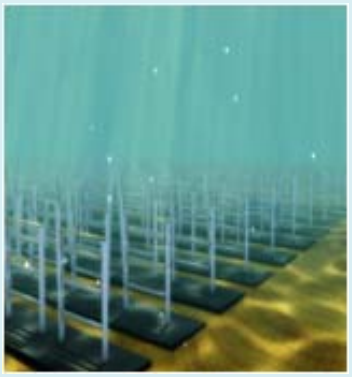
Vortex Induced Vibrations Aquatic Clean Energy: VIVACE, Vortex Hydro Energy (VHE) for NL in association with Tauw.

| | |
|---|---|
| **Brief description:** | Vortex induced transfer of hydro-kinetic into mechanical power. Claimed advantages are low cut-in speed and fish friendliness |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Extensive lab tests in USA, also on full scale in the USA. In the Netherlands tested on scale in de Oude IJssel @ Ulft |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Cp and Ct-values in the same range as for hydrofoils (free stream tidal turbines) (ref 1), possibly higher due VIV's (vortex induced vibrations) and galloping of successive cylinders.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Scale tested in de Oude IJssel Ulft. No report submitted yet.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** ... €/kWe.<br>• **O&M €/a:** not yet known |

**Remarks**

**References:**


1. Presentation given by prof. Bernistas (VHE), Tauw, Deventer, June 23. 2011
2. Confidential reports issued by mr. Gerard Pragt, Tauw, 20 March 2014

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Energie Fleuves SA, Rutten SA

| **Brief description:** | Propeller-type turbine, fixed runner blades |
|---|---|

**Schematics (cross-section and top-view):**

| **Technology Status:** | Unknown |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head:**

No data known yet.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Tested for fish friendliness in the river Maas (BE)

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** ... €/kWe.<br>• **O&M €/a:** not yet known |
|---|---|

**Remarks**

**References:**

1) Not possible to get into contact with Rutten SA or Energie Fleuves SA

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

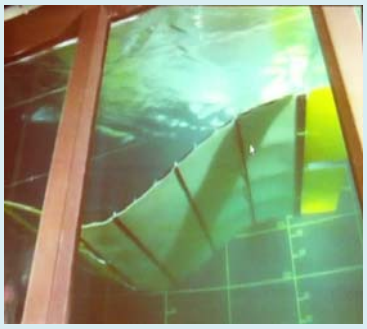
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Stingray, PulseTidal, BioStream (BioPower), Transverpello

| **Brief description:** | Oscillating hydrofoil devices |
|---|---|

**Schematics (cross-section and top-view):**

| **Technology Status:** | Stingray (full scale) , Transverpello (conceptual) , BioStream (laboratory) and membrane ondulante EEL Energy |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head:**

According to Wiemann, on the basis of Transverpello: Low efficiency 5 %. Research by WUR on Larval Zebrafish indicate a propulsion efficiency of 30 %, in the same range as for propellers.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Not known, likely to be fish friendly.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** ... €/kWe.<br>• **O&M €/a:** not yet known |
|---|---|

**Remarks**

**References:**

1. Wienmann, P, Review of Current Developments in Low Head Small Hydropwer, University of Southampton, http://hmf.enseeiht.fr/travaux/CD0708/beiere/3/html/bi/3/fichiers/Wiemann.pdf
2. Symposium Boulogne sur Mer, Membrane undulante.
3. Symposium Natural Solutions/Biomimicri, MARIN Wageningen, March 18, 2014

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

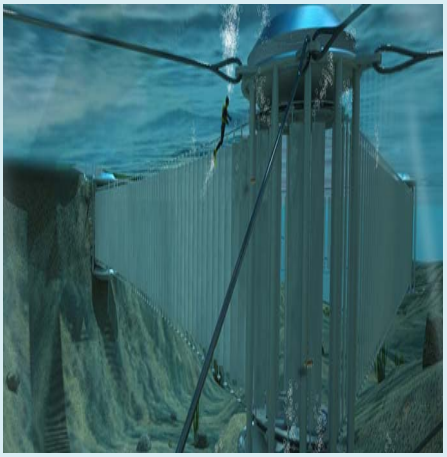
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Tidal Sails AS, Nereus Atlantis Resources, Natel SLH

| **Brief description:** | Transverse Lift machines |
|---|---|

**Schematics (cross-section and top-view):**




| **Technology Status:** | No commercial full scale application known. |
|---|---|

**Performance indicators:**

**Power output, in relation to hydraulic head:**

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Not known, likely to be fishfriendly.

| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** ... €/kWe.<br>• **O&M €/a:** not yet known |
|---|---|

**Remarks**

**References:**


*1)* www.**natel**energy.com; http://peswiki.com/index.php/Directory:Atlantis_Resources_Corporation_--_Nereus_and_Solon_Tidal_Turbines; http://tidalsails.com

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

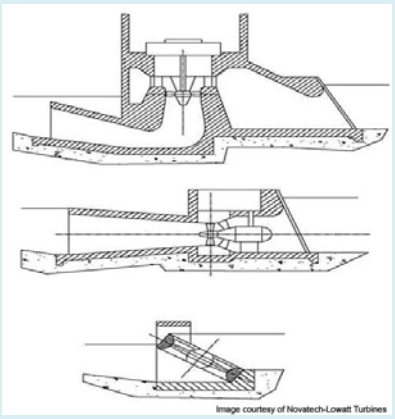
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Very Low Head (VLH), MJ2 technologies, FR

| | |
|---|---|
| **Brief description:** | Inclined pressure turbine, with relatively large diameter, slow-and variable speed Machine can also be installed vertically with horizontal turbine shaft |

**Schematics (cross-section and top-view):**




| | |
|---|---|
| **Technology Status:** | Applied in full scale in 40 projects, in France, and 7 more countries in Europe and Canada |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Claimed global efficiency in a range of 80 % from water to wire

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Full scale tested for fish friendliness, 0 % mortality for eels, up to 1-4 % for large rainbow trout

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** 3000 to 6000 €/kWe depending on head value including CW.<br>• **O&M €/a:** ~ 1 % of investment costs |

**Remarks**

- Can be modified for bi directional use, full frequency conversion allows bidirectional rotation of turbine and generator

**References:**

1. Interview with mr. B. De Ruiter, 25 March 2014
2. www.vlh-turbine.com/

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

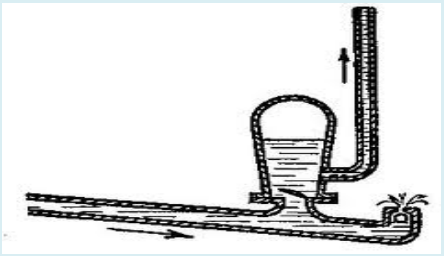
**Version: 07/07/2014 10:42**

**Name of the Technology, Manufacturer, Consortium:**

Water Ram, Hydraulic Ram, "Breur pump"; "Papa Pump".

| | |
|---|---|
| **Brief description:** | Creation of a (smaller volume) secondary circuit of high pressure water, due to in-stationary (impulse) of a periodically decelerating column of water. |

**Schematics (cross-section and top-view):**



| | |
|---|---|
| **Technology Status:** | Small units used for pumping water all over the World. Water can be lifted e.g. from 2 meters up to 10 meters.<br>As far is known never been used for tidal and hydropower generation |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Energy efficiency 60-80 %. Water volume fraction in that case 60-80 % times 2/10= 0,12-0,16.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

As far as known, not tested for Fish Friendliness, smaller 2nd medium can be screened for fish easily.

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis): Unknown** €/kWe<br>• **O&M €/a:** ... % of investment costs |

**Remarks**

**References:**


*1.* wikipedia.org/wiki/Hydraulic_ram

# Pro-Tide-NL Technology Factsheet

**Technical Coordinator J. Van Berkel**

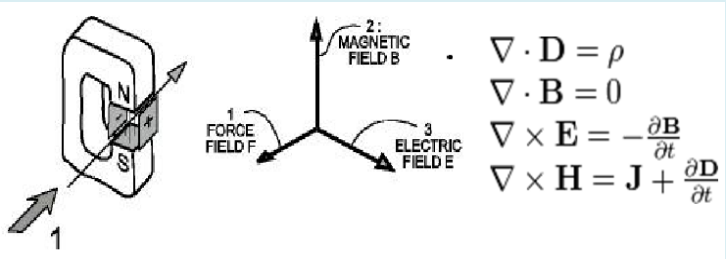
**Version: 07/07/2014 10:42**

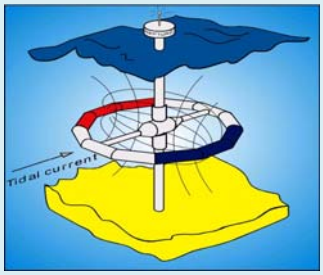
**Name of the Technology, Manufacturer, Consortium:**

Neptune MHD-Tidal Power Conversion, Neptune Systems.

| | |
|---|---|
| **Brief description:** | Following a concept of Faraday, tested at Waterloo bridge (1839), direct conversion of Hydro-kinetic energy into electricity, using sea water as the conductive medium. |

**Schematics (cross-section and top-view):**




| | |
|---|---|
| **Technology Status:** | Tested in laboratory using a torpedo (see picture above). Production of electricity demonstrated. Technique requires very strong superconductive magnets (> 6T) |

**Performance indicators:**

**Power output, in relation to hydraulic head:**

Power density relates to the square of velocity and Magnetic induction:

$$p = \frac{1}{4}\sigma\ u^2\ B^2\ \ [W/m^3]$$

.

**Fish friendliness, survival rate in relation to species. Demonstrated, proven by:**

Fish-friendliness researched by Imares (IJmuiden), no harmful effects identified

| | |
|---|---|
| **Costs: Hydro-electric conversion system:** | • **Investment €/kW-installed (prognosis):** > 5,000,- €/kWe (rough estimate)<br>• **kWh-costs** ~ 3,- €/kWh, for offshore conditions.<br>• **O&M €/a:** ... % of investment costs |

**Remarks**

**References:**


2. Neptune systems, 2003/2004, ftp://ftp.cordis.europa.eu/pub/sustdev/docs/energy/roman_yvette.pdf
3. https://www.senternovem.nl/mmfiles/0351-03-03-11-013%20Neptune%20Tidal%20converter_tcm24-188693.pdf