Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

# Climate Power Plant for Water Safety and Renewable Energy

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*Abstract*— **Barrage type tidal power plants, integrated with a pumping facility can be an effective measure to combine production of renewable electricity with protection of estuaries and adjacent area against rising sea water levels. The concept of such a "Climate Power Plant" is innovative, not demonstrated before.**

**The advantage of the concept is that one structure (civil works and pump/turbines) is multi-functional and a cost-effective measure to both adapt and mitigate to climate change.**

**This paper provides details about the design of laboratory set-up and the parametric design of a full scale system in the Brouwersdam as a part of the famous Dutch Deltawork. Test results of the scale model pump/turbine are elaborated and a theoretical model is described for full scale evaluation of the Brouwersdam system.**

**The paper also provides insights in how a Climate Power Plant can be realized in practice, by combining functions targeted at water safety, water level management and renewable electricity production. This type of innovative Delta technology needs to be developed in co-creation with partners in the next stage of the construction process. From an innovation literature perspective, a number of findings are shared that contribute to this pre-competitive co-creation process.The Climate Power Plant is a concept that potentially is relevant for Delta's all over the world.**

*Keywords*— **Climate Power Plant, Ultra Low Head Tidal Power, Water Safety, Pumping Turbines, Sustainable innovation management**

## I. Introduction

River Delta's are a cause, but also part of solution of climate change. Due to the fertile soil and access to sea, many people live in Delta's and strong economic activities like industry and agriculture take place. As a result, Delta's contribute substantially to Greenhouse gas emissions and changing climate. At the same time Delta's are very susceptible to the results of changing climate. Rising sea levels and increased river fluxes pose a threat to these delta's.

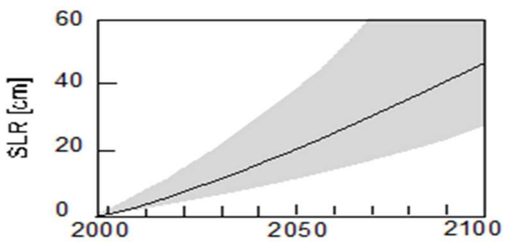


Fig. 1 Anticipated North Sea level rise, source (Awareness, 2019).

For centuries the sub-sea level in the Dutch Delta is protected from high waters by a system of dykes, pumping stations and storm surge barriers. Due to climate change however, sea level-rise occurs so fast that new measures must be taken according to the latest predictions (fig 1). Therefore it is essential to gain more knowledge and field lab experience to take adequate measures in the coming decades. One solution to adapt to the rising sea level is to build large pumping stations in the main waters.

Another development, fed by the transition process towards renewable energy, is to build tidal power plants in the Dutch Delta. Existing examples are operation of free stream turbines in the Afsluitdijk and Easterscheldt storm surge barrier. Since the late 1990, plans are investigated for a tidal power plant in the Brouwersdam. This dam closed the former estuary Grevelingen in 1971, but is now under consideration to be reopened for reintroduction of muted tides to improve water quality and subsequent the hole ecosystem in the Lake.

In his inaugural lecture at HZ University of Applied Sciences, Prof. J. van Berkel proposed to combine pumping stations and tidal power plants into one system. These "pumping tidal power plants" could be advantageous as the technical equipment (pump/turbines) is used for multiple purposes: 1) adaptation to climate change (pumping against rising sea levels) and 2) mitigation (generation of renewable energy). As the system addresses the cause as well as the result of climate change, the system was later termed "Climate Power Plant" by ir. A. Heutink. to facilitate the dialogue under policymakers.

At HZ University of Applied Sciences the Climate Power Plant is currently under investigation in a project called "Playing with Current(s)". The project focusses at the application of a very fast switching tidal power plant with a fourfold benefit:

1. Production of renewable electricity
2. Pumping, for storage and water level control (safety and ecology)
3. Electricity grid stabilisation by fast flexibility options (production and consumption of electricity)
4. Optimisation of lake destratification by pulse-wise flow operation

This paper focusses on the first two aspects. It outlines the experimental set-up that is built to demonstrate the technical functionality of the pump/turbines, and gives first results. It also describes the theoretical models that are developed to describe the dynamics of the system (basin) subject to real sea level data. As an example the model is applied to the Brouwersdam system.

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A Climate Power Plant not only is technically new and innovative. The Dutch water quality and safety is a public matter and production of electricity a private matter. Although policy making for renewable energy and climate is a public matter. Consequently the combination also demands for an innovative approach towards Pubic Private Partnership and an innovative co-evolutionary process. This innovative approach is treated in a separate section

## II. EXPERIMENTAL INVESTIGATION

To test and demonstrate the functionality of a Climate Power Plant (that can pump and generate electricity) a dedicated test set-up is designed and realised at HZ-University of Applied Sciences.

### A. General description

The test set-up comprises one head tank, representing the high water level basin and another tail tank representing the low water level basin.


Fig. 2 Climate Power Plant Simulator, laboratory HZ University of Applied Sciences.

The two tanks are connected by a conduit, housing a fast-switching valve and reversible propeller pump/turbine. Special feature of the pump/turbine is that the blades are symmetrical, principally providing equal hydraulic efficiency in forward and backward running mode. It is acknowledged that symmetrical blades constitutes a compromise in efficiency and that there is room for optimisation of efficiency both in pumping and turbining mode.

The pump/turbine is governed by a back-to-back frequency drive that can supply 3-phase electrical power from the grid to the pump, and feed-back 3-phase electrical power from the turbine into the electricity grid, both with variable frequency. It thus facilitates flexible 4-quadrant operation (forward/backward pumping/turbining).

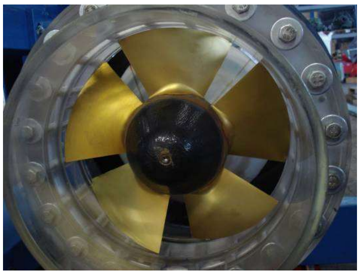

Fig. 3 Laboratory scale propeller pump/turbines, 30 cm diameter, manufacturer Pentair.

The control-unit also monitors and logs the set-up sensors. Of particular interest are the tank-bottom positioned pressure sensors from which the tank water levels are derived. The flow rate through the pump-turbine is derived from the temporal change of water level, knowing the plan area of the head- and tail- tank, respectively 4,4 and 9,2 $m^2$.

Power- demand or delivery is derived from torque (measured at the pump/turbine axis) and speed (rpm).

### B. In-stationary testing

Given the size of the pump/turbine and the tanks, a test lasts typically 40 seconds, meaning that the pump/turbine is subject to varying conditions (head and flow rate, the rotation speed is kept constant). A relevant question is whether performance data from this test represents pump/turbine-performance under practical conditions, with a much longer time-scale of typically ~6 hours between high and low water.

A criterion for acceptable time-wise variation is derived from an in-stationary-testing protocol of a Pelton-turbine, proposed by (Berkel, 1993).

In-stationary effects are represented by the Strouhal number Sr which is the ratio of in-stationary to stationary inertia forces.

$$Sr = \frac{\frac{\delta u}{\delta t}}{u.\nabla u} \qquad [-] \qquad (1)$$

For small Strouhal numbers, in-stationary flow effects are negligible and the flow may be considered as stationary. For this assumption to hold the Strouhal may not exceed the generally accepted value of 0.1 throughout the in-stationary test.

The magnitude of the Strouhal-number will be checked in the result-section of this chapter.

### C. Experimental result

Figure 4 gives a first result of a test with the Climate Power Plant simulator. Given is the system performance in pump mode: from low level (tail) water tank to the high level (head) tank.

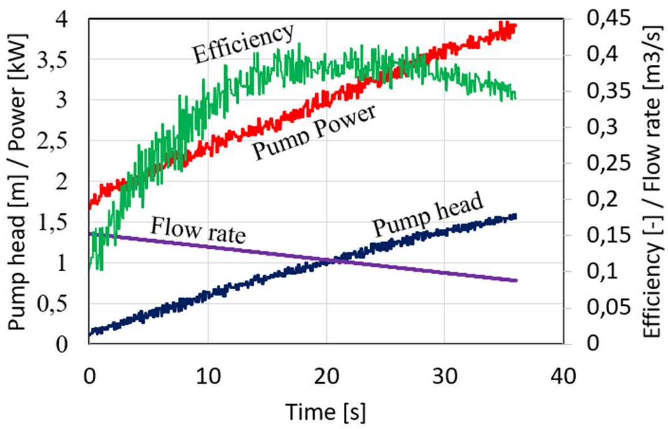


Fig. 4 Test results in pump mode (from tail tank to the head tank), for 750 rpm.

The graph shows that during the forward pump-test, power increases and flow rate decreases with the head, which is quite common for (fixed speed) rotary pumps.

Also displayed is the hydro-mechanical system efficiency, defined as:

$$\eta_{pump,system} = \frac{\Phi\, \rho\, g\, \Delta H}{P_{mech}} \qquad [-] \qquad (2)$$

Where

| | | |
|---|---|---|
| $\eta_{pump,system}$ | Pump system efficiency | [m] |
| $\Phi$ | Water flux | [$m^3$/s] |
| $\rho$ | Water density | [kg/$m^3$] |
| $\Delta H$ | Water level difference | [s] |
| $P_{mech}$ | Mechanical power need | [W] |

For the non-optimised set-up, hydro-mechanical system efficiency (including duct, valve and exit losses) reaches a maximum of 40 %.

Figure 5 gives the results for the reverse flow test (head tank to tail-tank) in which the direction of rotation of the machine is reversed (and set at 450 rpm).

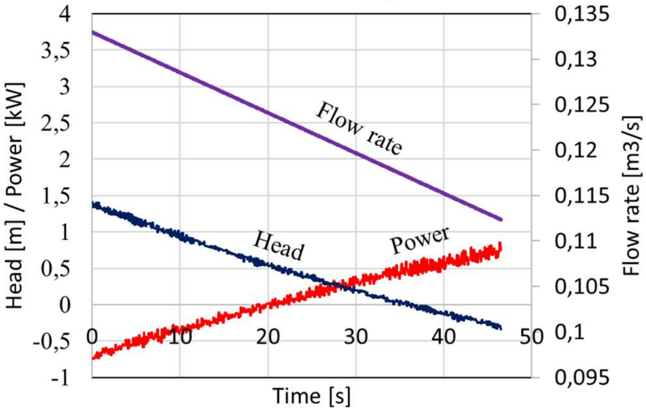


Fig. 5 Results for reverse flow (from head tank to the tail tank), for 450 rpm.

The graph displays that initially (up to 20 s) the machine operates as a turbine (requiring negative mechanical power=production). Notice that power production lasts up to a positive head of 0,5 m (zero efficiency), demonstrating that an ultra-low head is indeed possible, even in this small case non-optimised set-up. For full scale machines (factor 10 larger) the threshold is (much) smaller, as demonstrated by the hill chart figures for La Rance and Kislaya Kuba Tidal Power stations (Bernshtein, 1996).

From 20 s onwards the machine operates as a pump, first in gravity assisted mode (with positive head) and from 36 s onward in normal pumping mode (with negative head).

The graph thus in one view gives the machine in three modes, as further outlined in figure 6.

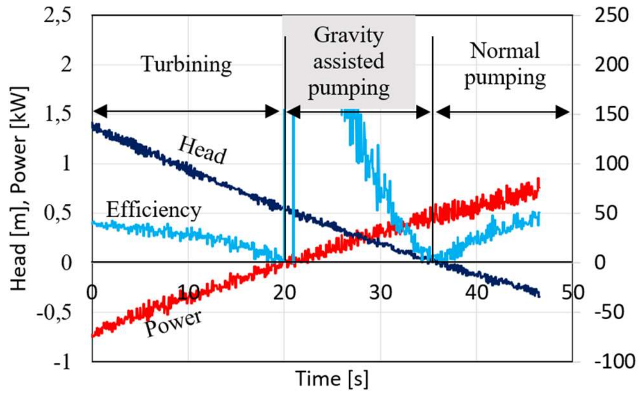


Fig.6 Results in reverse flow (from head tank to the tail tank), for 450 rpm.

In addition, to figure 6 gives the hydro-mechanical system efficiency, now defined as:

$$\eta_{turbine,system} = \frac{P_{mech}}{\Phi\, \rho\, g\, \Delta H} \qquad [-] \qquad (3)$$

In turbine mode, the system efficiency (including duct valve and exit losses) for this non-optimised set-up reaches a maximum of 50 % at 1,4 meter head.

An indication for full scale efficiency can be derived from the well-known Reynolds scaling law :

$$\frac{(1-\eta_{\text{turbine}})}{(1-\eta_{\text{model}})} = \left(\frac{\text{Re}_{\text{model}}}{\text{Re}_{\text{turbine}}}\right)^n \qquad [-] \qquad (4)$$

With the power factor n=0,1 as a conservative value. Assuming a factor 20 Reynolds ratio, the indication for full scale maximum efficiency is > 60 %. Note that this is a very tentative figure as further optimisation of the pump/turbine and test-up are ongoing.

Efficiencies (defined by 3) in gravity-assisted pump mode can attain very high values, well above 100%. In normal pump mode the scale model pump reaches an efficiency of 50 %.

Remaining questions is if this inherently in-stationary test provides results that are representative for stationary conditions.

Regarding in-stationary effects it must be noted that during reverse flow test the flow rate decreases from 0,135 m3/s to 0,115 m3/s in 46 seconds, which at a pump/turbine cross section of 0,07 $m^2$ corresponds with a deceleration of flow velocity of 6 $mm/s^2$. The velocity gradient in the conduit/pump turbine section typically is 1 $s^{-1}$, resulting in a convective acceleration of typically 3 $m/s^2$. The in-stationary acceleration divided by the convective yields a Strouhal number of 0,002, which is smaller than de 0,1 critical value. The in-stationary test results are representative for stationary conditions.

## III. Modelling

For proper evaluation the hydro-energetic performance of the turbine and the pump must be modelled. Input is the measured sea level at the location. Regarding the overall system dynamics, the water level in the basin lake Grevelingen is computed in a discrete manner, using an Euler-explicit time-integration:

$$H_{basint,t+\Delta t} = H_{basin,t} + \frac{\Phi\, \Delta t}{A_{basin}} \qquad [m] \qquad (5)$$

Where

| | | |
|---|---|---|
| $H_{basin,t+\Delta t}$ | Water level at time t+Δt | [m] |
| $H_{basin,t}$ | Water level at time t | [m] |
| Φ | Total water flux (at time t) | [$m^3/s$] |
| t | time | [s] |
| Δt | time-step | [s] |
| $A_{basin}$ | Surface area of the basin | [$m^2$] |

The water flux through the Climate Power Plant depends on the operation of the system and the water level difference across the dam.

### D. Turbine-mode

In turbine mode, the flow rate Φ, in relation to the water level difference across the dam follows the equations by (Berkel, 2015).

$$\Phi = N\, A_t\, C \sqrt{2\, g\, (H_{sys} - H_{turb})} \qquad [m^3/s] \qquad (6)$$

Where

| | | |
|---|---|---|
| N | Number of pump-turbines | [-] |
| $A_t$ | Cross-section area of the turbine | [$m^2$] |
| C | flow coefficient | [-] |
| g | Gravity constant | [$m/s^2$] |
| $H_{sys}$ | Total head available | [m] |
| $H_{turb}$ | Pressure head over the turbine | [m] |

And for power output, using the degree of reaction R:

$$P_E = \eta_t\, C\, \rho\, g\, A\, R_t \sqrt{1 - R_t}\, \sqrt{2\, g\, H_{sys}^3}\,[\mathrm{W}] \qquad (7)$$

Where

| | | |
|---|---|---|
| $P_E$ | Turbine electrical Power | [W] |
| $\eta t$ | Turbine hydro-electrical efficiency | [-] |
| $R_t$ | Turbine reaction $H_{turb}/H_{sys}$ | [-] |

### E. *Gravity-assisted pump-mode*

When operated in pump-mode, a distinction can be made between pumping with the naturally occurring gravity flow “gravity-assisted” or against the naturally occurring gravity flow “normal pump-mode”. In a system where naturally occurring spill-flow is just not sufficient anymore, e.g. due to rising sea-level, the first pump-mode to apply is the gravity-assisted pump-mode.

The flow rate/ head relation follows a similar line as for the turbine. Again assuming a degree of reaction $R_p$:

$$\Delta H_{turb} = R_p\, \Delta H_{sys} \qquad [\mathrm{m}] \qquad (8)$$

One arrives at the expression

$$\Phi = N\, A_p\, C \sqrt{1 + R_p}\, \sqrt{2\, g\, H_{sys}} \qquad [\mathrm{m^3/s}] \qquad (9)$$

Where

| | | |
|---|---|---|
| N | Number of pump-turbines | [-] |
| $A_p$ | Cross-section area of the pump | [$m^2$] |
| C | flow coefficient | [-] |

The reaction $R_p$; representing the pressure head that the pump “adds” to the naturally occurring flow, depends on the rated power of the pump and the flow rate through the system. Following a similar approach as for the turbine, the reaction is given (implicitly) by:

$$R_p \sqrt{1 + R_p} = \frac{P_E}{C\, \rho\, g\, A\, \sqrt{2\, g\, H_{sys}^3}} \qquad [\mathrm{W}] \qquad (10)$$

This equation can be solved iteratively and with (9) gives the flow rate Φ in gravity assisted mode.

Yet another similar approach holds for “normal pump-mode”. This mode would be applicable when gravity-assisted pump-mode is not sufficient any more. In normal pump-mode high pump-heads can be reached. This normal pump-mode will be added to the numerical model and published subsequently.

## IV. Application to the Brouwersdam-system

In the basic variant, the future structure comprises an opening in the existing Brouwersdam.

Fig. 7 Reference design of the future structure (Awareness, 2019).

The relevant question here is what the added value of pump/tubines is, compared to the basic variant (plain gates/conduits).

For calculation of the system dynamics, the theoretical model outlined in section III, is fed with the known sea level data on a 10-minute interval basis at measurement-pole “Brouwersdhavensegat-8”. As in the governmental project, the year 2009 is adopted as the reference year.

Figure 8 gives the water level fluctuation at the North Sea and Lake Grevelingen, for the reference system, a sluice-gate comprising 12 conduits, with cross section 8 x 8 $m^2$. The hydraulic characteristic of the sluice gate is expressed in a flow coefficient C of 1,1.

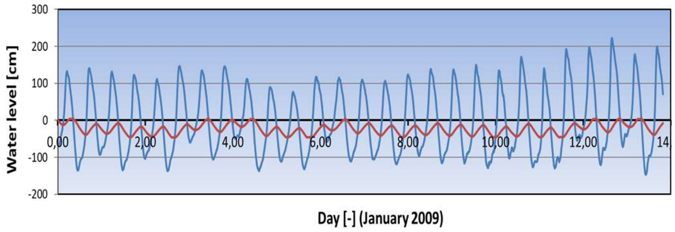


Fig. 8 Tidal dynamics: the blue line denotes the water at the North Sea (adjacent to the Brouwersdam) the red line the water level at Lake grevelingen.

Note that sluice-gates are operated such that the water level at Lake Grevelingen (red line in figure 8) respects the limits given in table 1:

TABLE I
Water level restrictions at Lake Grevelingen (RWS, 2018)

| | |
|---|---|
| Upper limit | 5 cm +NAP |
| Lower limit | 45 cm -NAP |
| mean | 20 cm -NAP |

Due to the asymmetry between the mean water levels at Sea and in the Lake, water enters lake Grevelingen easier than it exits. When built in the baseline configuration (conduits with gates) the required eb-flow determines the size of the sluice gate (number of conduits). To avoid rushing in during flood (as a result of the higher water head during flood), some gates must be partly or fully closed. The associated hydraulic loss is dissipated in (thermal) energy, and wasted.

Turbines could convert this hydraulic loss into electricity. The calculation model shows that in turbine mode, the Climate Power Plant can generate roughly 60 GWh/year. An added benefit of the turbines is that they can provide extra water safety (by flow control), and also provide an accurate means to control the water level in lake Grevelingen.

As the turbines can also operate as pumps, the Climate Power Plant can function also as a pumping station, thereby reducing the required number of conduits. In the gravity assisted pumping mode the rated power is more or less equal to the rated power in turbine mode. Figure 9 gives the required number of gates, for the basic system and the system with gravity-assisted pumping.

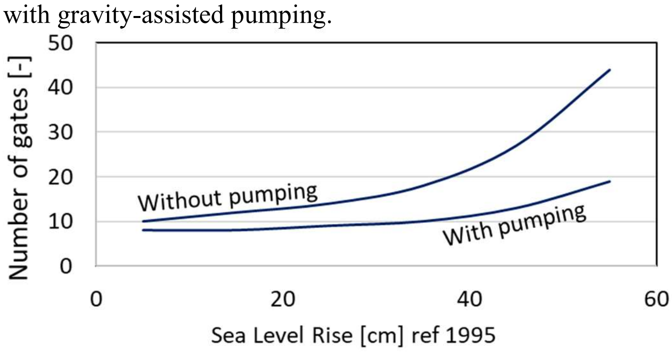


Fig. 9 Required number of conduits for the Brouwersdam system, with- and without pumping, with level requirement according to table 1.

The graph shows that pumping significantly reduces the size of the structure or (at a given size) can support the water level requirement in lake Grevelingen much longer.

Pump/turbine operation is done in an alternate sense: Turbining in flood-mode and pumping in ebb-mode, depending on sea level rise. Figure 10 displays the dependency on sea level rise, for as base-case Climate Power Plant with 12 gates.

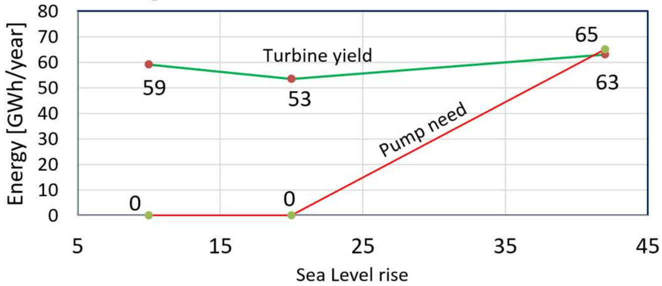


Fig. 10 Turbine yield and pump need, depending on the sea level rise, for a Climate Power Plant in the Brouwersdam, with 12 conduits.

Figure 10 implicates that up to a sea level rise of 20 cm (reference year 1995), pumping is not required to attain the required water levels at Lake Grevelingen. In turbine mode, the Climate Power Plant can generate between 59 and 53 GWh/year. Initially the turbines operate bi-directional mode. With the rising sea level there is less room for turbining in ebb-mode and the turbines gradually operate in full flood-mode.

Above a sea level rise of 20 cm, pumping becomes more and more necessary. At a sea level rise of somewhat more than 40 cm, annual pump energy approximately equals annual turbine yield. In that sense it can be stated that up to a sea level rise of 40 cm the Climate Power Plant is nett energy positive.

This recognisance shows that application of Climate Power Plants could be an attractive solution to both adapt and mitigate climate change.

Regarding costs and financial benefits work is ongoing. For the Brouwersdam as an example, it can be stated that for a sea level rise of 40 cm, implementation of pump/turbines roughly halves the required number of gates, in principle from 20 to 11. On the other hand, pump/turbines would imply added costs. Current insight indicates that regarding investments, increased pump costs level with reduced civil costs (Awareness, 2019). The added benefit of electricity production (roughly without added costs) can make the business case positive.

Work is ongoing: more research must be done on technology, ecology and economy (financial benefits and costs). The presentation at the EWTEC-conference will provide more detail on these matters.

## V. Innovation toward sustainability

Governments and policy makers face major societal challenges in the areas of sustainability, climate control, and renewable energy transition. These challenges can come together for improving the water quality of the lake Grevelingen and subsequent the ecosystem in the form of a climate power Plant. This generates energy for 17,000 households, saves 30 Kton $CO_2$ annually and is primarily capable of regulating the water level and quality of the lake for the next 100 years, despite the 40 cm (reference year 1995) rise in sea level. Latest results show in comparison circa 20 years without the pump/turbines. In addition the annual cost saving is prognosed to be 50-70 M€ according to the latest prognoses by preventing additional investments.

An innovation system is seen as a set of distinct interconnected institutions which jointly and individually contribute to the development, creation, diffusion and implementation of knowledge, skills and artefacts. As such the Climate Power Plant is an artefact in a niche within a sectoral system of innovation in the construction sector (Egmond et all, 2008, Malerba, 2004). The strategic niche management theory can be used to facilitate the transition to sustainable innovations by creating technological niches and a protected project environment with its own set of starting points. Such niches are assumed to make an important contribution as building blocks for a wider social change towards a sustainable future (Schot and Geels, 2010).

In the case for the Brouwersdam-system, actors in the network have worked together intensively to investigate the possibilities for a Climate Power Plant. The government and market parties have examined the feasibility in various market consultations. This has resulted in various designs, business cases, purchasing strategies, dynamic modelling in Joint Fact Finding sessions and an in-depth understanding of how policy makers can create a protected project environment with its own set of preconditions. The results are described in (Awareness, 2015, 2018 and 2019). This has created a broad knowledge base about the feasibility of a Climate Power Plant. Risks for a feasible business case are; Subsidies, water level management and sea level rise and the future electricity price. A controlled building process in which the government and the market cooperate intensively with a go/no-go moment are essential preconditions.

The case study of lake Grevelingen and the Brouwersdam Climate Power Plant has allowed the government and the market to jointly be able to shed more light on the preconditions under which this innovation becomes possible. This co-evolutionary process allows government to fulfil the ambitious social tasks they are facing toward a sustainable and new delta technology with global exposure.

## VI. Conclusions

This recognisance study shows that application of Climate Power Plants is an attractive solution to adapt and mitigate to climate change.

1. Experiments demonstrate:
   a) that (even on small scale), an integrated pump/turbine is suitable for turbining, gravity assisted pumping and pumping,
   b) at ultra-low heads 0,5-1,5 m,
   c) and for a non-optimised configuration at maximum efficiencies (prognosed full scale) of > 60 %.
2. The in-stationary testing procedure proves to deliver results that are representative for stationary conditions.
3. Application of a Climate Power Plant is beneficial, as it:
   a) Produces renewable energy.
   b) Provides Water Safety by pumping.

c) Offers better control of the basin water level

4. The concept of the Climate Power Plant is considered new and innovative delta technology with global impact.
5. With reference to the Brouwersdam system, application of a Climate Power Plant is expected to be a costs-effective and safe solution. The Climate Power Plant reduces the size of the sluice-gate, and/or elongates the functional lifetime of the structure.
6. Public Private Partnership is case of the Climate Power Plant is challenging, seen the different economic and ecologic interests.
7. Co-evolutionary process between the government and the market leads to a joint broad technological knowledge base and a better understanding of the risks and opportunities for a Climate Power Plant.
8. The primary goal of robust improvement of the water quality and ecosystem of Lake Grevelingen can economically speaking best be served with a Climate Power Plant. Therefore the preconditions have to be created in the niche of tidal powers plants.
9. More research is needed of the Climate Power Plants, on technological-, economical ecologicaly and governancial- preconditions and the process of how to generate these .
10. There is a potential for further applications of Climate Power Plants, in (estuarine) Delta areas all over the World.

## Acknowledgment

Investigations described in this paper are performed within the framework of the project "Playing with Current(s)", supported by SIA. It is based on the former EU Interreg project Pro-Tide. Public information regarding the Getij Grevelingen and Tidal Power plant is gratefully provided by the Dutch Ministry of Infra Structure and Water management, Rijkswaterstaat.

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