TECHNICAL FEASIBILITY OF ENERGY CONVERSION FROM SALINITY GRADIENTS ALONG THE DUTCH COAST; A CASE STUDY AT IJMUIDEN

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In the mixing process of water with different salinities a large amount of energy is released, which is normally converted into heat if fresh water rivers enter estuaries and seas. This energy, often referred to as Blue Energy, may be extracted by two different processes: Reversed Electrodialysis (RED) or Pressure Retarded Osmosis (PRO). The Netherlands has a number of locations where large fresh water flows enter saline water bodies via man-made structures, creating opportunities for Blue Energy applications. This paper investigates the hydrodynamic and mass transfer processes at two different scales, the estuarine scale and the membrane module scale, for a specific site in The Netherlands: IJmuiden. The physics at these two very different scales both play a role in the performance of a potential Blue Energy power plant.

On the estuarine scale – the tidal and density driven hydrodynamic scale – the performance of a Blue Energy power plant depends primarily on the available salinity gradient. In many locations, natural mixing of saline and fresh water reduces the maximum exploitable salinity gradient. Therefore, an adequate intake and outfall layout is required to optimize the performance of a Blue Energy plant. Particulate matter content is another issue to be addressed: at present, the required pre-filtration would account for the largest energy losses in the Blue Energy process. A model at the module scale shows that delicate balances exist between most of the design parameters of a Blue Energy power plant and that for salinity gradients present in IJmuiden a net energy production in the order of 5 to 7 MW can be expected.

INTRODUCTION

Due to a growing demand on electric power, the scarcity of fossil fuels and the associated CO_2 release new energy sources are explored. One of the prospective new sources is Blue Energy, which is the production of energy from the mixing of fresh and salt water. In the Netherlands there is a huge potential for the application of Blue Energy (see e.g. Deltares, 2008). A total flow of 3000 m^3/s of fresh water is discharged on average into the North Sea. From this total discharge, part could be used for generation of Blue Energy. Locations which are potentially suitable are the Afsluitdijk (400 m^3/s), the Haringvliet (750 m^3/s) and the North Sea Canal (95 m^3/s), where civil works cause a separation between salt and fresh water. The main focus of this paper is the North Sea Canal. The Dutch Rijkswaterstaat's (RWS, Directorate General for Public Works and Water Management) ambition is to have the locks and pumping station operate exclusively on energy that comes from renewable sources by the year 2020 in order to cut carbon dioxide emissions. The realization of a Blue Energy plant may contribute to this.

At present, there are two known techniques to harvest Blue Energy: Reversed Electrodialysis (RED) and Pressure Retarded Osmosis (PRO), for more details see e.g. Post (2007). This paper concentrates on the PRO technique; the reason for this being our experience with Reverse Osmosis (RO), the reversed process of PRO. In the PRO process fresh water and salt water are separated by a membrane. The osmotic pressure difference over the membrane drives the fresh water to the salt water side, causing the pressure on that side to increase. A turbine then converts the potential energy into electrical energy. This technique was first developed in the 1970's by Loeb (Loeb, 1979) and has since then been under investigation. In 2009 Statkraft opened the first pilot plant of 10 kW for osmotic power using PRO (Statkraft, 2009). The technique has thus come a long way and might be promising for a power plant at the North Sea Canal sluice complex in the future.

This paper aims to investigate the technical feasibility of a Blue Energy power plant at IJmuiden. In a first step the local environmental conditions are analyzed and computations on an estuarine scale are performed to verify the available salinities in the vicinity of the sluice complex. The results of these computations are used to determine the performance of a PRO power plant by applying a model describing mass balances on the module level – the membrane scale –. The outcome of this model is an optimum mixing ratio of salt and fresh water for the available salinity gradient. The resulting salt and fresh water intake flows and brackish discharge is then fed back to the estuarine model to investigate the effects on local flow patterns and the risk of recirculation of brackish outfall water.

SYSTEM DESCRIPTION

The North Sea Canal connects the Port of Amsterdam to the North Sea. Although the canal was initially constructed for shipping purposes, gradually it gained importance in the Dutch water management. The North Sea Canal drains a catchment area covering a significant part of the Netherlands (2300 km^2). The surplus of water is discharged into the North Sea through the flushing and pumping station at IJmuiden (see Figure 1).

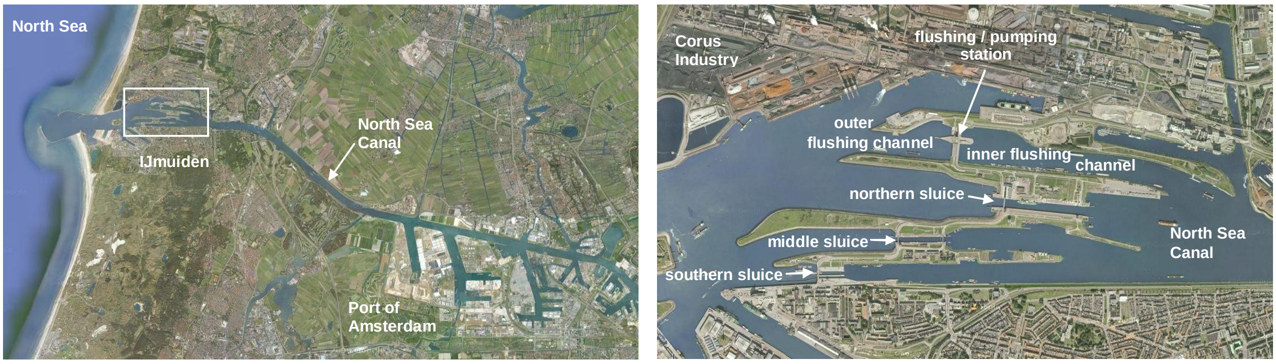

Figure 1. North Sea Canal (left) and IJmuiden sluice complex (right). Source: Google Maps.

The mean discharge at IJmuiden is 95 m^3/s, but the daily average discharge varies over the seasons with low discharges of 40 m^3/s in dry periods to over 200 m^3/s in wet periods. In times of low to normal discharges, the flushing gates can handle the outflow; for higher discharges the pumping station comes in operation. Because of the limited time interval around low tide at sea, when flushing is possible, the instantaneous discharges are significantly higher than the daily averages, varying from 0 to a maximum of 500 m^3/s. The target level in the North Sea Canal is -0.4 NAP (Dutch Ordnance Datum), with a tolerance of -0.55 to -0.3 m NAP. The water level is controlled by smart flushing and pumping at IJmuiden. Flow velocities in the canal fluctuate with the discharge rates at IJmuiden and generally range between 0 and 0.4 m/s.

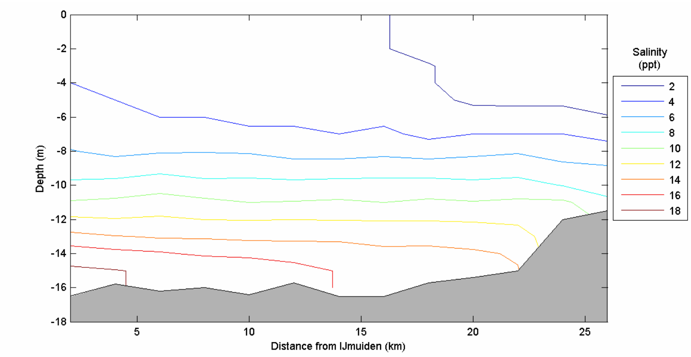

Figure 2. Average salinity distribution over the North Sea Canal based on monthly measurements collected in 1994 and 1995

The North Sea Canal is a brackish system with a vertical salinity gradient. Salt is supplied to the canal by lock exchange flows at IJmuiden. In each lock cycle, a net amount of salt water enters the canal, contributing to a salt wedge that extends over 20 km in eastward direction. Fresh water of lower density moves in the opposite direction at the surface of the canal, thus causing a net circulation flow. Vertical exchange between the top and bottom layers makes that the top layer gradually becomes more saline in the western part of the canal. The mean salinity distribution over the channel is given in Figure 2, based on field data collected in the years 1994 and 1995 by RWS.

On its western end, the North Sea Canal is connected to IJmuiden's outer harbour and the North Sea through a complex of navigation sluices and a flushing and pumping station. The outer harbour covers an area of approximately 4 km^2 and has an entrance width of 800 m. The main navigation channel is approximately 20 m deep. Two harbour moles extend 2.5 km into the sea on a furthermore straight sandy coast. The tidal range is 1.5 to 2 m, with tidal currents outside the harbour ranging from 0.5-0.7 m/s for an average tide. Within the outer harbour, especially close to the flushing station, the currents are influenced by the fresh water discharge from the North Sea Canal. When the full flushing capacity is used, velocity magnitudes in the order of 1-1.5 m/s occur locally.

The North Sea has an average salinity of about 35 ppt. However, along the Dutch coast the salt content is strongly influenced by the fresh water outflow of the rivers Rhine, Meusse and the Scheldt. The plumes of these rivers cause a body of relatively fresh water to move northward along the coast with a strong cross-shore salinity gradient. Depending upon the river discharges and wind, the width of the plume varies from a few to over 40 km (see e.g. de Boer, 2008) Within the outer harbour of IJmuiden, a strongly layered system exist. A flow of relatively fresh water moves outward in the surface layers, its thickness depending on the tide and North Sea Canal discharge conditions. A more saline inward flow is permanently present in the lower layers, with vertical exchange of salinity with the top layers. A density driven circulation flow is thus present in the outer harbour.

COMPUTATIONAL MODEL - ESTUARINE SCALE

To gain insight in the spatial salinity distribution and temporal salinity variations in the outer harbour, numerical model computations were performed on what we call the estuarine scale. This scale describes the dynamics by the tide and the density gradients in the entire harbour complex. For the hydrodynamic modelling Delft3D-FLOW was used. This program was developed for modelling of unsteady water flow and transport of dissolved matter in shallow seas, coastal areas, estuaries and rivers, see e.g. Lesser *et al.* (2004). Delft3D-FLOW solves the shallow-water equations for given initial and boundary conditions in two or three dimensions. The continuity and the horizontal momentum equations are solved by an implicit finite difference method (ADI) on a staggered grid. For the vertical grid, a σ-coordinate approach is used. The momentum transfer and mixing by 3D turbulence subjected to density gradients is represented by the k-ε turbulence model.

The existing operational IJmond-model of RWS was used in this study, initially set up to simulate the water motion along the northwestern part of the Dutch coast. The model is forced by tides, storm surges and input of river discharges. For this study, the 2DH model was converted into a 3D sigma layer model to resolve the vertical salinity distribution and stratified flow in the outer harbour. To achieve this, salt transport was introduced into the model. The IJmond model grid is a curvilinear grid encompassing the harbour of IJmuiden and the surrounding North Sea. The along coast distance is approximately 85 km and the cross-shore distance approximately 30 km. For this study, the resolution in IJmuiden's outer harbour was increased to accurately resolve the complex water motion due to tides and flushing and sluice activities. The grid resolution varies from about 500 m on the edges of the grid to about 20 m around the sluice complex near IJmuiden, see Figure 3. The total number of active grid cells is about 60,000 in 10 equidistant sigma layers over the vertical.

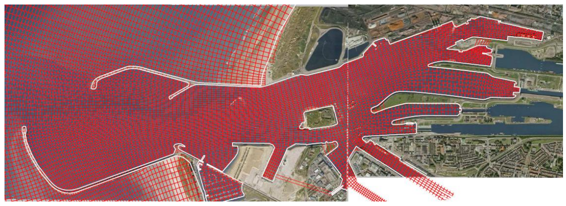

Figure 3. Detail of computational grid in the outer harbour of IJmuiden

The IJmond model is forced with Riemann boundary conditions along the sea boundaries, which are obtained by nesting in the Kuststrook Model (the coastal zone model by RWS describing the entire Dutch coastal system). A mean tidal scenario with an average discharge from the North Sea Canal (95 m^3/s) was considered for this study. Discharge boundary conditions were imposed for the flushing and pumping station and the lock exchange flows. The fresh water flow from these sources were simulated as pulsating discharges in the top layers to represent the tidal dependency of flushing and the intermittent lock activities. The salinity of these discharges was set at 6 ppt, the observed average salinity in the top half of the North Sea Canal. The salt boundary conditions at sea were constant in time and included a gradient on the cross-shore boundary from 28 ppt to 35 ppt to incorporate the effect of the coastal river plume as discussed above.

The operational IJmond model of RWS has been extensively calibrated; for the harbour of IJmuiden a mean RMSE value in tidal water levels of 0.11m is reported. Using the experience with similar models along the Dutch coast, the 2DH model was converted into a 3D salt model. Although the 3D model was not further calibrated for its salt distribution, a qualitative comparison with scattered data in the vicinity of IJmuiden provided the required confidence for application in the present study.

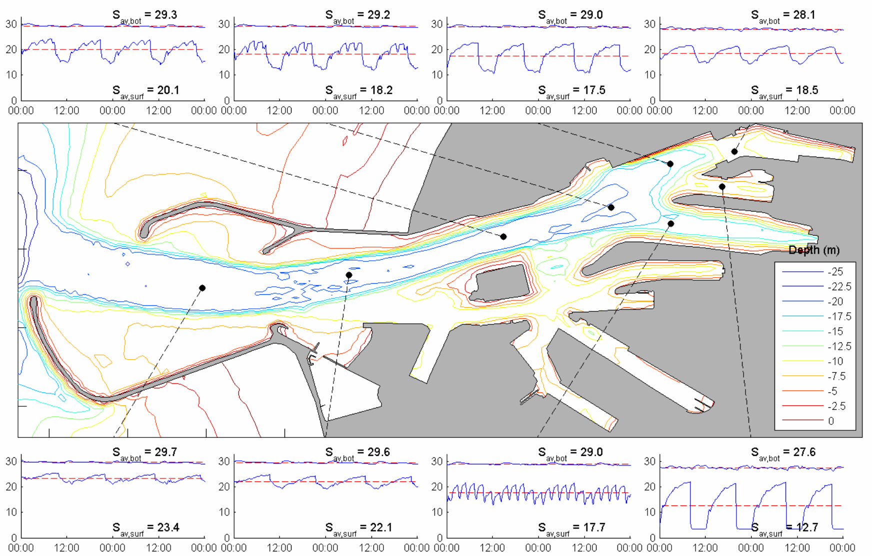

Figure 4. Computed salinity distribution in the outer harbour, with indication of the bed level contours.

Based on model simulations the salinity distribution in the outer harbour of IJmuiden was investigated. A clearly layered salinity distribution is observed, see figure 4. Strong variations in surface salinities are apparent on a tidal timescale, related to the ebb tidal flushing, and on an hourly timescale, related to lock operation. The pulsating fresh water inputs have less effect on the bottom salinities. The highest salinities are found at depth in the navigation channel closest to sea. Near the sluice complex an average bottom salinity of 28-29 ppt is found, further seaward increasing to 29-30 ppt. The model confirms the 3D density driven circulation pattern in the harbour; along the bottom of the navigation channel a net inflow of saline water exist whereas a permanent outflow of fresher water in the top layers is present.

COMPUTATIONAL MODEL - MODULE SCALE

The computed salinity distribution in the outer harbour served as input for a performance analysis at the module scale. For the calculation of the plant's performance, the model as described by Zwan *et al.* (in press) was used. In this model, the performance of a PRO power plant is computed based on mass balance considerations on the module level. The performance of commercially available membranes is determined based on characteristic membrane parameters. Zwan *et al* show that Nano Filtration (NF) membranes can be used in the PRO process instead of Reverse Osmosis (RO) membranes. NF membranes have larger pores compared to RO membranes. This results in an increased water flux through the membranes, yet also an increased salt flux. The net result is a lower power output per unit area. The main advantage of NF membranes is the reduction in the required salt water pre-treatment. Such pre-treatment is necessary to remove particulate matter to avoid blockage of the membranes. As Zwan *et al.* show, the energy consumption of the salt water pre-treatment can be in the order of 25% of the gross power output. As the outer harbour has a high content of fine material (see e.g. Winterwerp, 2003), the use of NF membranes is favourable for the net energy output at IJmuiden. In the calculations, an average fresh water flow rate of 40 m^3/s and application of NF membranes has been considered.

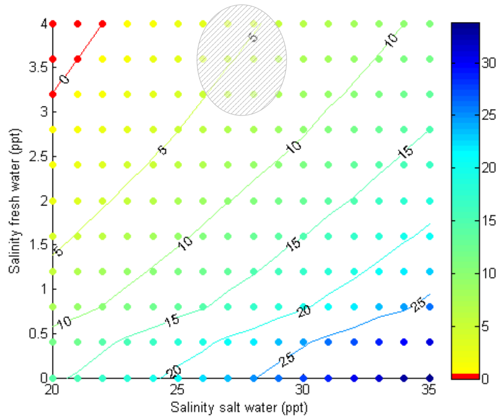

Figure 5. Net power output (MW) as function of the fresh and salt water salinity

With these input parameters, the net power output was calculated for a range of fresh and salt water salinities. For each combination the optimum operating point in term of trans-membrane pressure, fresh water cross flow velocity and salt-water mixture ratio was determined. Figure 5 shows the net power output for all the salinity combinations. In the optimal case – fresh water of 0 ppt, salt water of 35 ppt – the net power output is 34 MW. The grey area shows the available salinities around the sluice complex (surface North Sea Canal and bottom outer harbour) and indicates that a net power production can be achieved. The computed maximum power output is 8.5 MW based on a salinity gradient of 25.5 ppt (3.5 - 29 ppt). For these conditions, it is computed that a total salt water flow of 110 m^3/s is required, giving a fresh to salt water ratio of 1:2.8. If less salt water is used, the salinity on the salt water side would decrease and the external concentration polarization would increase (less mixing). These effects reduce the water flux through the membrane, hence the net power output.

In the calculation of the flux through the membrane, the ratio between the salinity of the fresh and salt water is taken into account; the higher this ratio the lower the flux. As a similar change in salinity leads to a larger relative change in salinity for fresh water than for salt water, a salinity reduction of the fresh water will be considerably more effective to increase the net power output than a salinity increase of the salt water.

COMBINED MODEL RESULTS

A Blue Energy power plant will affect the salinity distribution and flow patterns in the surrounding water system. Potentially, this could have an have adverse effects on the available salinity gradient, thereby reducing the efficiency of the plant. With the salt water intake and brackish discharge computed by the model at module scale fed back to the estuarine model, such effects could be investigated.

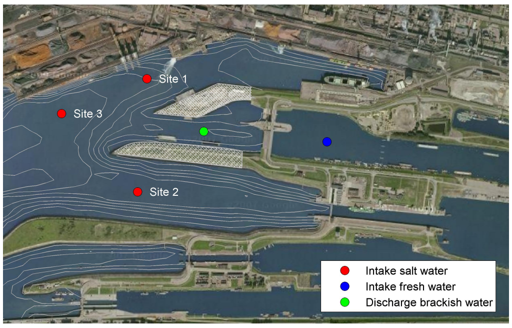

Figure 6. Intake and outfall locations considered in the estuarine scale model. The dashed areas indicate potential sites for a Blue Energy plant.

In the considered scenario for this simulation, the extraction of 40 m^3/s fresh water (~3.5 ppt) from the North Sea Canal and 108 m^3/s salt water (~29 ppt) from the outer harbour is considered. The 40 m^3/s fresh water input is the minimum daily average discharge from the North Sea Canal. In the scenario, the average flushing discharge of 95 m^3/s is consequently reduced to 55 m^3/s. The total discharge of brackish water (22 ppt) of 148 m^3/s is released in the outer flushing channel. This location is chosen as it will alter the hydrodynamic conditions in the outer harbour least compared to the present situation, thereby minimizing any negative side effects on navigation.

The sluice complex is owned by RWS, making it a viable location for the plant. The two most promising construction sites are indicated in Figure 6. These were chosen based on their proximity to the flushing station, where the infrastructure to take in fresh water is present and where brackish water can be released, and to the navigation channel, where the highest salinities are found. Three alternative salt water intake locations (see figure) were considered to assess the potential salinity gradient and recirculation effects. The depths at the three sites are -15.5, -17.2 and -19m NAP respectively.

The intake of fresh water from the North Sea Canal does not lead to significant changes compared to the present situation – in the canal, the discharge is more evenly distributed over time, so peak velocities are reduced and an overall more constant flow pattern is the result – and is not discussed any further. In contrast, the flow patterns in the outer harbour are significantly affected by the salt water extraction and simultaneous brackish water discharge. During high water (HW), the vertical circulation in the outer harbour will be intensified due to the permanent discharge of brackish water, assuming no discharge of the flushing / pumping station under normal conditions at HW. During low water (LW) conditions, the circulation slightly weakens compared to the present situation because of the reduced fresh water discharge. Along the bottom of the navigation channel, an increase in inward directed flow velocities is observed for all three alternatives in the order of 0.1-0.2 m/s maximum, which is an increase of about 25% (see Figure 7, showing alternative 1). The increase in velocities at the surface is especially pronounced during HW (+0.3 m/s), when in the present situation no fresh water is discharged. However, the absolute magnitude of the outward directed flow velocities is still much weaker than during LW. At that moment, an additional volume of fresh water is flushed from the canal leading to velocities in and around the outer flushing channel in the order of 1 m/s.

The difference in flow patterns between the three alternatives is not pronounced; especially the surface flow patterns are very similar. Along the bottom, differences exist locally around the salt water intake points, but at a small distance from these locations, the differences become negligible.

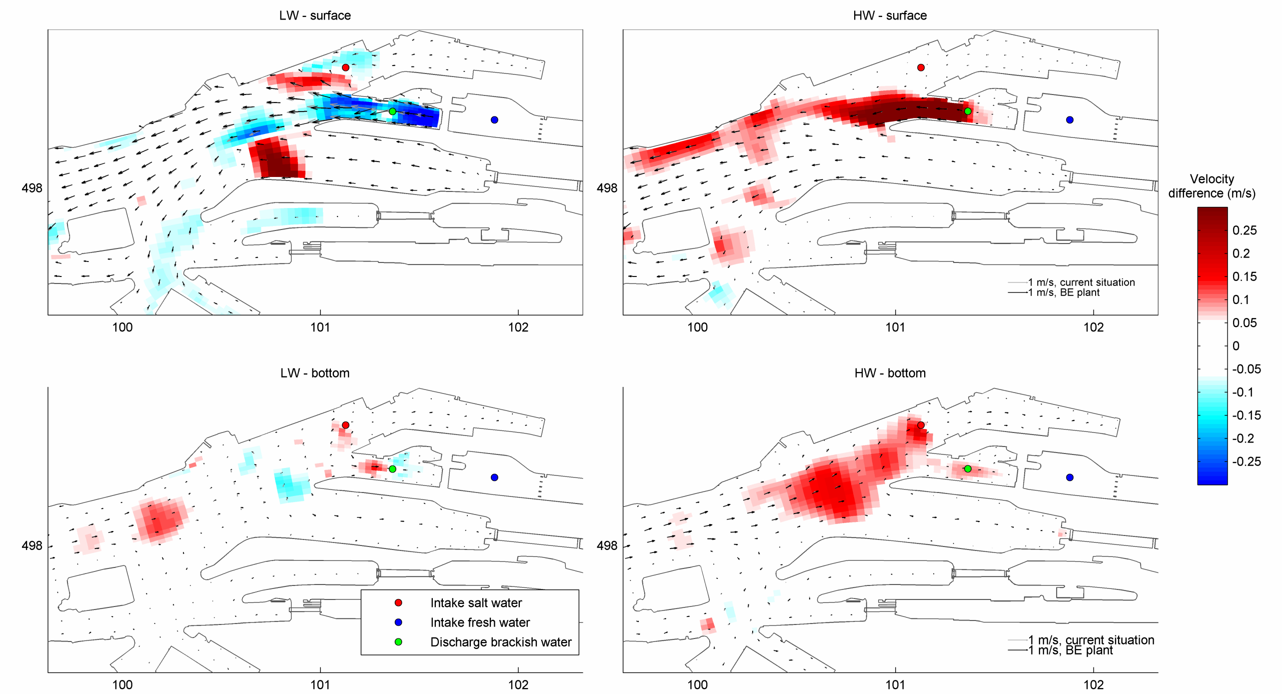

Figure 7. Computed flow patterns at LW and HW compared to the present situation for alternative 1

Recirculation of the discharged brackish water is not desirable for the efficiency of the Blue Energy plant. Recirculation occurs when the salt water intake draws in part of the brackish water, effectively reducing the salinity potential to be utilized by the plant. Figure 8 presents near bed salinities at the salt water intake location (alternative 2) compared to the present situation without a plant. The observed reduction in salinity is due to two effects; the main one being recirculation and a secondary one being the vertical drawing in of water from higher layers with lower salinities. This latter effect is a near field phenomenon that the present model does not accurately resolve. It would be highly dependent on the design and layout of the intake installation, but as it plays a minor role it is not further investigated here. The average reduction in salinity is in the order of 0.5 ppt with a maximum of approximately 0.7 ppt. For alternative 1, the reduction is slightly higher, whereas for alternative 3 it is close to zero. This only limited effect of recirculation can be explained by the two layer system in the outer harbour that rapidly transports the brackish water to the open sea and that continuously supplies salt water through the deep navigation channel.

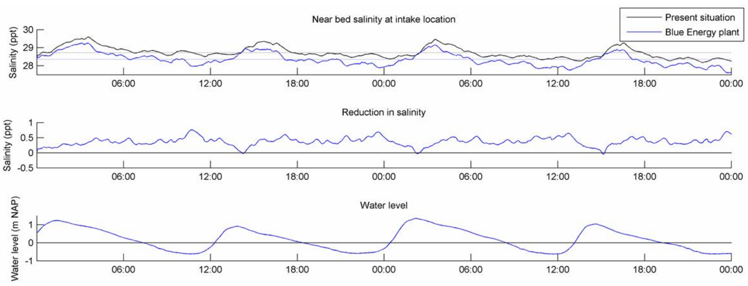

Figure 8. Computed near bed salinities at the salt water intake location, alternative 2.

CONCLUSION AND DISCUSSION

It is concluded that the sluice complex at IJmuiden provides an opportunity for a Blue Energy plant because of the sharp separation of fresh and salt water and the continuous outflow of fresh water. On the seaward side, a virtually limitless amount of salt water is available. The sluice complex would be an excellent location for a plant; infrastructure to take in fresh water and release brackish water is readily accessible and salt water is available close by. The salinity gradient is large enough to achieve a net energy production in the order of 5 to 7 MW. However, a small change in salinity of either the salt or the fresh water would result in a decrease of net power. It is therefore of importance to maintain the salinity gradient and to minimize recirculation flows. It is shown that without an optimized design, recirculation leads to a reduction in gradient in the order of 0 - 1 ppt. It is believed that this can be further reduced or possibly completely avoided with careful optimization of the intake and outfall locations and layout. This should be investigated with dedicated numerical modelling, describing near field phenomena around the intake structure and plume behaviour around the outfall structure.

Additionally, it is recommended to explore the exploitable salinity gradient. It was argued that especially a reduction of the fresh water salt content leads to a considerable gain in energy output. Potential measures to achieve this can be:

- Avoid salt intrusion into the North Sea Canal; several techniques to reduce salt transport through lock complexes exist. As salt intrusion is the main salt input for the canal, a less brackish system would be formed.
- Make use of fresh water from nearby sources, e.g. industrial cooling water, effluent of waste water treatment plants or the flow of pumping stations draining the surrounding polders. A side benefit is that the particulate matter content of this water will probably be low and energy consumption for pre-treatment will be reduced.
- Take in water further upstream in the North Sea Canal where salinities are lower.

An increase in gradient can likewise be achieved by taking in more saline water further offshore. Obviously, the energy losses associated with the transport of water should be offset against the effective gain in energy production.

The design of a Blue Energy power plant involves complex management issues. Both the North Sea Canal and the outer harbour have several functions with potentially conflicting interest. The main task of the harbour and the canal – shipping and water management – are not to be affected by the plant's operation. The impact of flushing flows on ship maneuverability has always been a main point of attention. The positioning of the intake and discharge points of a Blue Energy plant should therefore receive careful attention in relation to safe navigation to the quays and locks. A possible beneficial effect is the reduction in peak flow velocities, as the tidal dependent flushing rates are partly replaced by a constant power plant discharge. As was shown, this reduces the velocities especially in the surface layers, which is advantageous to navigation. Regarding water management, it was assumed that the minimum daily average discharge of 40 m^3/s can be utilized. It must be verified whether this amount can be guaranteed at all times; e.g. with an expected increase in drier summer months this amount could potentially be significantly lower in future. The plant will probably be last in line to receive fresh water in times of high drinking water, irrigation or water level management demands. On the other hand it can be argued that the plant is effectively a water management tool; it can be considered as an energy-neutral pump transporting water from the canal to sea, whilst producing energy in the process.

Solely based on a consideration of salinity and discharge characteristics and specific properties of the PRO technology, a Blue Energy plant is expected to be technically feasible at the IJmuiden sluice complex. Many other issues, such as environmental aspects (ecology, siltation, navigation), technical aspects (membrane technology, pre-filtration) and economic aspects (green energy subsidies, membrane prizes, kilowatt-hour rates), will eventually determine the overall viability of a Blue Energy plant and need profound investigation. But first and foremost, the Blue Energy technology needs further development. The PRO technology is now at the pilot stage and several issues still need to be addressed before application at the full operational scale becomes realistic. Firstly, the performance of RO and NF membranes needs to be verified by measurements. Secondly, investigation of the pre-treatment is required, in which the experience of the RO industry can be helpful. Finally, a comprehensive comparison of the PRO and RED technology should be made to determine which technique is favorable for given site conditions.

ACKNOWLEDGEMENTS

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