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DOI
10.1088/1742-6596/1618/3/032015

Publication date
2020

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: F. Greco *et al* 2020 *J. Phys.: Conf. Ser.* **1618** 032015

Preliminary design of a hydraulic wind turbine drive train for integrated electricity production and seawater desalination.

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Abstract.
The integration of wind energy to desalinate seawater can address the freshwater scarcity issue and alleviate the environmental impact of desalination. This paper presents the use of the Delft Offshore Turbine, an unconventional wind turbine with hydraulic transmission which can be used to directly drive a seawater reverse osmosis desalination process and to produce electricity with a Pelton turbine. A steady-state model is used to identify the potential regions at which it is possible to operate the system and to propose a system settings for maximising water production. The results show that the proposed system provides up to 300 kW of electricity and can desalinate up to 25 m^3/h, at rated operating conditions.

1. Introduction

1.1. Wind powered desalination

Seawater desalination is an effective solution for alleviating the freshwater scarcity problem [1]. On the other hand, desalination is a high energy consuming process, and the use of fossil fuels to power desalination plants contributes significantly to the intensification of CO_2 emissions [2]. The integration of wind energy to drive seawater desalination has the potential to mitigate the environmental impact and to satisfy the high demand of power required for freshwater production [3].

Previous work has already been carried out on wind driven desalination. The majority of the work presented in literature requires wind energy conversion into electricity to power the desalination process, [4, 5, 6] or energy storage system for power smoothing, [7]. A case of a prototype in which the intermediate electrical conversion was avoided is described by Liu [8, 9], in which the multivane windpump was able to raise up enough pressure for desalinating brackish water, but not seawater. A small-scale windpump driving seawater desalination was developed in [10]. In this project the seawater pump was located at the bottom of the tower and was connected to a 6.2 kW multivane wind turbine by means of a bevel gear and a vertical shaft. It produced up to 0.5 m^3/h with a 25% recovery rate.

1.2. DOT500kW Pilot Reverse Osmosis (PRO) Project
Delft Offshore Turbine (DOT) develops an innovative wind turbine with hydraulic power transmission [11, 12]. This technology can be used to directly provide the high pressurised seawater for the reverse osmosis process, with the aim to make freshwater production from wind energy more simple and cost-effective [13]. Moreover, part of the pressurised water could be used for electrical power production by means of a Pelton turbine generator [14]. Hence there is the flexibility to adjust the system output between electricity and freshwater depending on the required demand.

The use of wind energy for seawater desalination presents the challenge of combining a wind turbine, which is a highly dynamic system, with reverse osmosis desalination, which is typically operated under relatively stationary conditions. A reverse osmosis desalination unit can work in a very narrow range of conditions and cannot be easily switched on and off, since flushing of the system is required to prevent damage of the membranes. This operating mode clashes with the stochastic nature of the wind resource. Therefore, the integration of a wind turbine with desalination unit requires a fundamental understanding of each component's limits and their interactions.

Within the DOT500 PRO Project, DOT plans on developing, building and testing their hydraulic wind turbine for both water and electricity production. A pilot demonstration of this project is scheduled for installation and commissioning in the first half of 2021. The pilot plant will be composed of a 44 meter rotor diameter wind turbine, retrofitted with a high pressure pump. The hydraulic power transmission system will feed a seawater reverse osmosis desalination unit with a capacity of 600 m^3/day of permeate and a Pelton turbine.

The goal of the research presented in this paper is to identify the system settings that allow for maximum freshwater production under a given system configuration. The potential regions of operation are identified taking into account the safe operation of the wind turbine, the required electricity production to power the auxiliary equipment, and the highest amount of freshwater production within the physical and chemical constraints given by the reverse osmosis process and membranes. A mapping of the operating settings is proposed to maximise the production of freshwater and electricity within the potential regions of operation.

2. Description of the wind driven desalination system
The system can be subdivided in three main subsystems, that will be described in this section: the hydraulic wind turbine, the electricity production subsystem and the freshwater production subsystem. A schematic of the system is shown in figure 1.

2.1. Hydraulic wind turbine
The hydraulic wind turbine consists of a three bladed horizontal axis wind turbine whose generator in the nacelle has been replaced by a positive displacement pump. In this way, it is possible to relocate the heavy components, like the generator and the power converters, to ground level, resulting in a higher accessibility. Further elaboration on hydraulic wind turbines with their advantages and disadvantages is presented in [11, 12].

In the proposed system, the rotor converts the energy extracted from the wind into rotational motion. The motion is transmitted through the shaft to the high pressure pump, that pressurises the seawater and directs it to the electricity and water production subsystems. The high pressure pump has a nominal flow of 2417 l/min at nominal rotation speed of 28rpm.

2.2. Electricity production system
A portion of the pressurised seawater is deviated towards a spear valve and dedicated to electricity production. The function of the spear valve is to convert the pressurized flow into kinetic energy in the form of a high speed water jet, that is finally converted into electrical

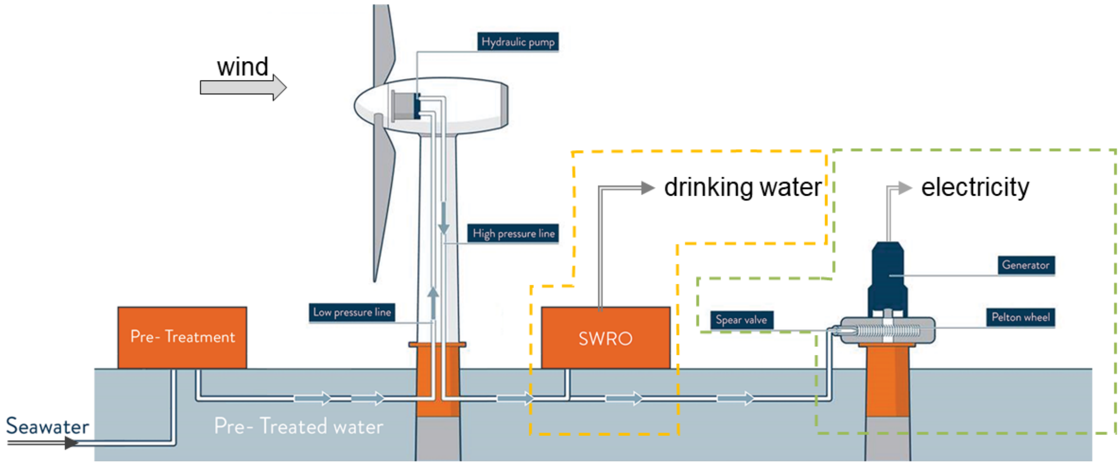

Figure 1: Schematic showing the main components of the wind driven seawater reverse osmosis (SWRO) system. Courtesy of DOT B.V.

energy by the use of a Pelton turbine and a generator. The spear valve is constituted by a spear that, moving in and out a nozzle, varies its orifice area. By adjusting the effective area of the nozzle, it is possible to control the pressure of the flow and the speed of the hydrodynamic jet supplied to the Pelton [14, 11].

2.3. Freshwater production system

The freshwater production group is composed of the seawater reverse osmosis (SWRO) desalination unit, that actively separates salts (brine) from freshwater, and the isobaric energy recovery device (ERD) that extracts the high residual pressure energy in the brine.

Reverse osmosis is a water purification technology driven by pressure [15]. When seawater and freshwater are separated by a selective membrane, i.e. a membrane that only allows the passage of pure water and retains salt, ions and other particles, the difference in salt concentration generates a driving force that pushes the pure water from the low concentration (freshwater) side of the membrane to the high concentration (seawater) side, until the balance is reached. The water pressure on the seawater side of the membrane at equilibrium conditions is defined as the osmotic pressure. The osmotic pressure increases with the increase in the concentration. For seawater, with an average total dissolved salts (TDS) concentration of 35000 mg/l, the osmotic pressure is around 30 bar. In the reverse osmosis process, when an external pressure, higher than osmotic pressure, is applied on the high concentration side, pure water is forced to pass through the membrane to the low concentration side, proportionally to the difference between the applied pressure and the osmotic pressure. For seawater desalination, usually the pressure applied is between 55 and 68 bar [15].

In SWRO desalination systems, spiral wound membranes are often used. More membranes can be placed in series after each other, so the brine exiting from one membrane becomes the feed flow of the following one. The series of membranes, up to eight in a row in case of seawater, is enclosed inside a pressure vessel. More pressure vessels can be connected in parallel to increase the capacity of the system. For the study of this paper, a six by six configuration is adopted.

Since the pressure drop along the pressure vessels is limited to a few bars, the brine still has a high energy content at the exit side. The ERD is a device that allows to recover the energy in the brine by exchanging pressure between the brine and feed seawater. The ERD is made of a perforated rotor in a sleeve and two end covers. On one end, low-pressure seawater enters

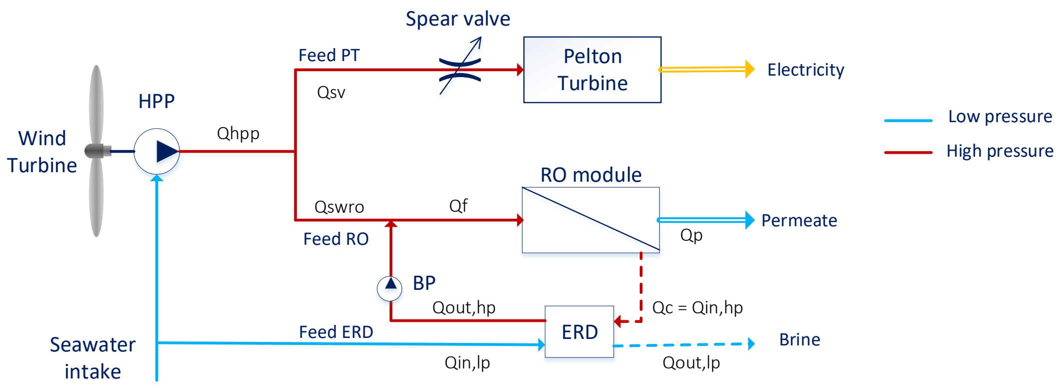

Figure 2: Schematic of the system showing the flow rates in the main points of interest. Solid lines represent seawater, the dashed lines represent the brine and the double lines represent permeate (in blue) and electricity (in yellow)

the ERD and flows in the perforated ducts of the rotor (solid blue line in figure 2). During the rotation, the feed seawater is briefly exposed to the high pressure brine, entering from the other end (dashed red line). The brine transmits its energy to the seawater and pushes it out from the ERD (solid red line). Simultaneously, the low pressure brine is pushed out of the ERD (dashed blue line) by the feed seawater entering the ERD (solid blue line). This cycle repeats continuously with each rotation. A boost pump is used with the high pressure seawater line to compensate for the pressure losses. The high pressure line is brought up to the same pressure as of the seawater coming from the high pressure pump, to be fed to the SWRO unit. The use of the ERD increases the efficiency of the system, but can also contribute to control the operation of the desalination unit as will be described in section 5.

2.4. Control of the system
The integrated system described above can be actively controlled in three different manners:

- The collective blade-pitch mechanism, to adjust the rotational speed and the power extracted by the rotor
- The spear valve of the Pelton turbine: by moving the spear in the nozzle, the available area is varied which allows to modify the pressure and consequently the flow through the spear valve.
- The ERD: by adjusting the seawater flow rate exiting the ERD to modify the recovery rate of the desalination unit.

3. Design criteria and constraints
Desalination plants and wind turbines are typically operated differently. SWRO desalination plants are usually designed to operate under stationary conditions with relatively constant flow rates. They work at one operating point, corresponding to rated conditions, and during the production the system is only allowed to slightly deviate from the selected operating conditions. For the DOT hydraulic wind turbine, the high-pressure pump with constant volumetric displacement (HPP) delivers a flowrate proportional to its rotational speed. The pump flow is therefore a function of the wind conditions. As a consequence, the reverse osmosis (RO) module is subjected to a varying feed flow, preventing it to operate at a unique and fixed

operating point. A series of operating points per wind speed has to be defined, within the limits and constraints of each component.

The limits and the possible range of operation that are described in this section are shown in figure 3. The dashed lines represent the pressure-flow curves corresponding to the aerodynamic torque on the rotor for each constant wind speed. The aerodynamic torque is translated to pressure by means of the high-pressure pump with constant volumetric displacement.

3.1. Safe operation of the hydraulic wind turbine

The operation of the wind turbine is limited by the cut-in and cut-out wind speeds. In between, two different operation modes can be identified [16].

From cut-in wind speed up to rated wind speed, the wind turbine gradually increases its rotational speed, as well as its power production and the torque applied. For any change in wind speed, the torque exerted by the high pressure pump counteracts the aerodynamic torque, to find a new equilibrium point. The region of instability, that is simplistically represented in figure 3 on the left side of the maximum torque line, must be avoided [14]. At rated wind speed and above, the rotational speed of the rotor and the power produced are kept constant by actively controlling the pitching of the blades. In this case, the high pressure pump is operated at steady conditions.

Regarding the high pressure pump, the main constraint is given by its maximum rotational speed, which is related to the maximum feed flow delivered by the volumetric displacement pump. This coincides with the right limit of the horizontal axis shown in figure 3.

3.2. Desalination system limits and constraints

The SWRO unit is a very delicate part of the system. The constraints can be subdivided in two types: more stringent limits and less stringent limits. Limits of the former type are imposed to prevent the membranes failure. Limits of the latter type, if exceeded, imply a faster wear or more frequent maintenance of the membranes, and are not described in this paper.

In the first group, the osmotic pressure draws the dotted bottom limit in figure 3. If the fluid pressure entering the SWRO unit is lower than the osmotic pressure it is not possible to obtain any permeate. On the other hand, natural osmosis may occur, if not prevented by safety measures. The permeate may flow through the membrane in the opposite direction, causing a loss of product and the damage of the membranes, that are not designed for the reverted flow. Since the concentration of the feed increases moving along the pressure vessels, also the osmotic pressure increases accordingly. Thus, the bottom boundary line is set to be higher than the osmotic pressure corresponding to the concentration of seawater at the inlet of the pressure vessel.

The upper limit is given by the maximum pressure that the membranes can withstand to avoid mechanical failure, usually around 83 bar (top dotted line in figure 3). Regarding the flow, a feed flow higher than the maximum allowed can cause the so-called telescope effect, which is the shifting of the membranes layers towards the end covers, due to the excessive drag forces generated by the water flow. This effect destroys the membrane. Similarly to the high pressure pump, the ERD limitations for maximum and minimum flowrates were considered.

3.3. Safe operation envelope for wind driven desalination

All the constraints described before delimit a portion of the graph area in figure 3 where it is possible to safely operate the SWRO subsystem. Considering such constraints, the final goal is to maximise fresh water production while producing enough electricity to power the auxiliary equipment of the system, i.e. to make it independent from any external energy sources.

The recovery rate has to be kept as high as possible in order to maximize the permeate, taking into account the concentration of the feed water. The water concentration on the feed-brine side increases as the water moves along the membrane proportionately with the recovery rate. A high recovery rate combined with a high feed concentration might lead to an oversaturated brine, which will cause scaling at the end of the pressure vessel.

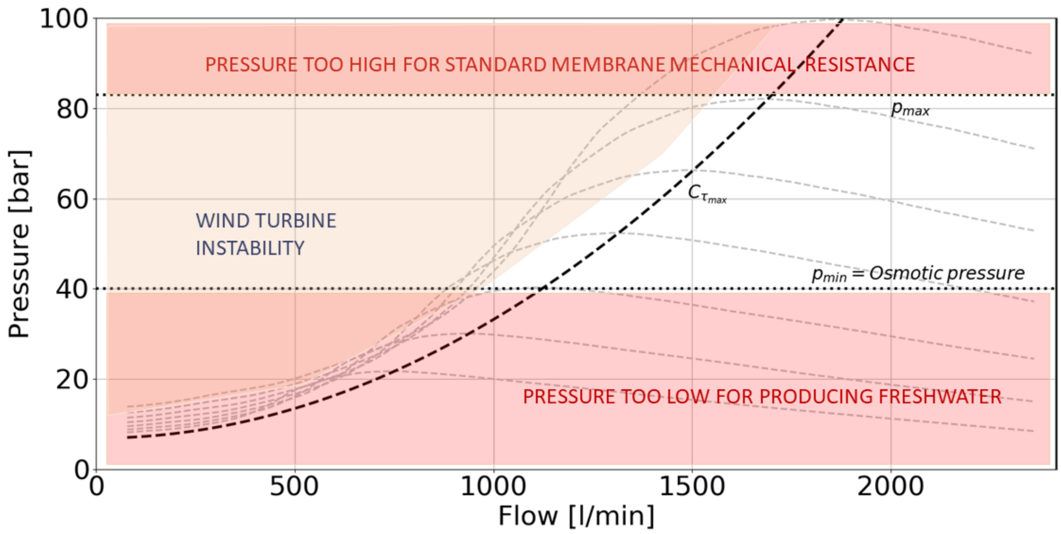

Figure 3: Limits of the hydraulic wind turbine (in orange) and of the freshwater production subsystem (in red) with respect to the pressure-flow curves of the rotor (in grey)

4. Numerical model of the wind driven desalination system

A numerical model has been developed to describe the steady state behaviour, including the interactions between the components as shown in figure 2. Hydraulic lines and the additional pressure losses through pipes are not considered in the simplified model, since their impact is slightly affecting the system for the operating conditions. The integrated model is based on physical principles for each of the components and their interaction using the fundamental principles of conservation of mass, energy and momentum.

4.1. Hydraulic wind turbine

The wind energy is extracted by the wind turbine rotor and transmitted to the high pressure pump (HPP). At equilibrium conditions, the torque of the wind turbine acting on the shaft must be equal to the torque exerted by the high pressure pump. The aerodynamic torque of a horizontal axis wind turbine can be expressed as a function of the wind speed U, the air density ρ_{air} and the rotor radius R_{rot}, as in equation 1 [16].

$$\tau_{aero} = \frac{1}{2}\,\pi\,\rho_{air}\,R_{rot}^3\,U^2\,C_\tau(\beta,\lambda) \tag{1}$$

$C_\tau(\beta,\lambda)$ is a non dimensional coefficient, called torque coefficient, and is a function of the pitch angle of the blades β and the tip speed ratio λ, that is the ratio of the rotor tip speed to the free wind speed.

The high pressure pump converts the rotary motion in a pressurised seawater flow, as follows:

$$Q_{hpp} = V_{d,hpp}\, \omega_{hpp}\, \eta_{hpp,vol} \tag{2}$$

where ω_{hpp} is the rotational velocity of the pump and $\eta_{hpp,vol}$ is the volumetric efficiency, which takes into account the volume loss relatively to the total displaced flow, and it is assumed constant for the considered range of operating conditions.

The transmitted torque of the pump is expressed as the product of the volumetric displacement $V_{d,hpp}$ and the pressure difference across the pump, Δp_{hpp}:

$$\tau_{hpp} = \Delta p_{hpp}\, V_{d,hpp}\, \frac{1}{\eta_{hpp,mec}} \tag{3}$$

where $\eta_{hpp,mec}$ is the mechanical efficiency of the pump, considering the friction losses. The pressure downstream the high pressure pump is determined by the minimum flow resistance provided by the spear valve and the SWRO unit. The flow processed by the high pressure pump is directed to the electricity production subsystem and to the SWRO unit:

$$Q_{hpp} = Q_{sv} + Q_{swro} \tag{4}$$

4.2. Electricity production system

The flow that passes through the spear valve and that acts on the Pelton turbine is given by equation 5, which results from the manipulation of Bernoulli's equation for incompressible flow:

$$Q_{sv} = C_d\, A_{eff,sv} \sqrt{\frac{2\Delta p_{sv}}{\rho_w}} \tag{5}$$

where C_d it the discharge coefficient and takes into account pressure losses attributed to the geometry of the valve and flow regime, Δp_{sv} is the pressure difference over the spear valve, ρ_w is seawater density and $A_{eff,sv}$ is the effective nozzle area, that depends on the relative position of the nozzle with respect to the circular surrounding nozzle area, as described in [14].

4.3. Water production system

The reverse osmosis unit is modelled as a series of membrane elements located in a pressure vessel; several pressure vessels are connected in parallel. The system parameters refer to each membrane unit. The total mass balance and a salt mass balance per membrane element are expressed in equations 6 and 7 respectively, where Q represents the volumetric flow, while C the salt concentration; the subscripts f, p, and c refer to feed, permeate and concentrate of each element.

$$Q_f = Q_p + Q_c \tag{6}$$

$$C_f\, Q_f = C_p\, Q_p + C_c\, Q_c \tag{7}$$

The reverse osmosis model considers the solution-diffusion theory for the mass transfer across the membrane [15, 17, 18], in combination with empirical equations to account for concentration polarization F_{cp}, the influence of temperature, expressed by the temperature correction factor, F_{tc}, among others. Concentration polarization represents the tendency of formation of a higher concentration layer next to the membrane surface, and locally increases the osmotic pressure. According to this model, the permeate flow can be expressed, as shown in equation 8, as a function of pressure difference between the system p and the osmotic pressure π, also defined as net driving pressure Δp_{net}.

$$Q_p = F_f\, F_{cp}\, F_{tc}\, \frac{K_w A_m}{\rho_w}\, (\Delta p - \Delta\pi) \tag{8}$$

$$\Delta p_{net} = \Delta p - \Delta\pi = (p_{in} - \frac{p_{drop}}{2} - p_p) - (\bar{\pi}_{fc,iel} - \pi_p) \tag{9}$$

where Δp and $\Delta\pi$ represent the pressure and osmotic pressure difference between the two sides of the membrane; F_f is the flow factor, indicating the wear and the fouling of the membrane which depends on its age; A_m is the membrane area; p_{in} is the pressure of the flow at the inlet of the membrane, p_{drop} is the pressure drop along the membrane; $\bar{\pi}_{fc,iel}$ is the average osmotic pressure on the seawater side of the membrane. The water permeability, K_w, is a membrane dependent parameter, and represents the tendency of the membrane to let water permeate through it.

The osmotic pressure, that strongly depends on the concentration of the solution, also depends on the water temperature T_w as expressed in equation 10.

$$\pi = \delta\, T_w\, C \tag{10}$$

where δ is an empirical constant [18]. Another important parameter that characterizes the membrane is the rejection R, describing the ability of the membrane to prevent the salt passage, in equation 11. Nowadays, membranes can reach a rejection as high as 97-99%, that means that only the 1-3% of salts are passing through the permeate.

$$R = 1 - \frac{C_p}{C_f} \tag{11}$$

An indication of the amount of freshwater produced with respect to the water fed to the desalination unit is the recovery rate γ, that is given by the ratio between the permeate and the feed flow rates:

$$\gamma = \frac{Q_p}{Q_f} \tag{12}$$

The efficiency of the ERD operation is affected by mixing and overflush [19]. Mixing M is due to the lack of a physical barrier between the brine and the seawater inside the ducts. It describes the exchange of salts from the brine to the seawater at their interface. Mixing affects only a very small layer of fluid and it is limited by the contact time of the fluids. Therefore, it decreases by increasing the rotational speed of the ERD. Its definition is given in equation 13. As a result of the mixing, the concentration of $Q_{out,hp}$ is slightly increased, and therefore, also of the feed seawater to the membranes .

$$M = \frac{(C_{out,hp} - C_{in,lp})}{(C_{in,hp} - C_{in,lp})} \tag{13}$$

Overflush is a parameter that indicates the difference between $Q_{in,lp}$ and $Q_{out,hp}$. A higher overflush limits the mixing. On the other hand, it requires more power to feed the ERD with a higher flow.

The mass and salt balance for the ERD are expressed in equations 14 and 15

$$Q_{in,hp} + Q_{in,lp} = Q_{out,hp} + Q_{out,p} \tag{14}$$

$$C_{in,hp}\, Q_{in,hp} + C_{in,lp}\, Q_{in,lp} = C_{out,hp}\, Q_{out,hp} + C_{out,lp}\, Q_{out,lp} \tag{15}$$

A few assumptions are taken into account in the model. For the sake of simplicity, the required overflush is neglected. Second, following the conservation of mass in the sleeves of the ERD perforated rotor and for the correct operation of the ERD, the high pressure brine flow $Q_{in,hp}$ and the high pressure seawater flow $Q_{out,hp}$ are considered equal, except for leakages, which are in this paper assumed negligible.

$$Q_{in,hp} = Q_{out,hp} = Q_c \tag{16}$$

The most significant consequence on the overall water production subsystem is that the permeate flow Q_p results equal to the flow Q_{swro}, according to the conservation of mass:

$$Q_{swro} = Q_f - Q_{out,hp} = Q_p \tag{17}$$

In other words, the permeate produced depends only on the flow coming from the high pressure pump, and it is independent from the feed flow. Therefore, given Q_{swro}, the recovery rate is only affected by the feed flow, that is in turn determined by $Q_{out,hp}$. As a consequence, it is possible to regulate the recovery rate of the SWRO unit by controlling the high pressure seawater flow exiting the ERD $Q_{out,hp}$ [13]. The design of the system and of the control strategy is built on this relevant conclusion.

5. Mapping of the proposed steady-state operation

The results presented in this section are obtained by combining and solving the system of equations of the numerical model presented in section 4. In table 1 all the input parameters are listed. A mapping of the proposed steady-state operation is defined considering the limited area of possible operation as well as the requirements defined in section 3, . The mapping is shown in figure 4 by a thick red line. The letters A, B, C, D identify the points where the control switches to different modes. The results in terms of freshwater and electricity produced and consumed by the system, for each wind speed are shown in figure 5.

Table 1: Design parameters and values used for this study

	Parameter	Unit		Parameter	Unit		Parameter	Unit
ρ_{air}	1.225	kg/m^3	$V_{d,hpp}$	1.61	l/rev	F_f	0.85	-
ρ_w	1025	kg/m^3	$\eta_{hpp,mec}$	0.90	-	K_w	3.43/1e9	s/m
C_{sw}	38000	ppm	$\eta_{hpp,vol}$	0.93	-	M	0.06	-
T_w	10	℃	N_{pv}	6	-	δ	0.2641	Pa/ppm K
R_{rot}	22	m	N_{mem}	6	-	γ	0.40	-
β	0	deg	A_m	40.9	m^2			

For the wind speeds at which the resulting pressure on the system is below osmotic pressure (trait 0-A in figure 4), water production is not possible. Hence, all the flow processed by the high pressure pump is directed to the Pelton turbine for electricity production. Passive control is implemented and the spear valve is set to the opening position that maximise power extraction of the wind energy by the rotor [11, 20] (on top of the green line in figure 4).

At a wind speed of 4 m/s the threshold is reached for the system to produce enough power to satisfy the electricity needs. Above that wind speed, the power produced by the system is higher than the power consumed by the system.

In point A, the required wind speed to start water production is reached at 7 m/s. With the current setting of the spear valve, the resulting pressure is still below osmotic pressure. However, by closing the spear valve it is possible to obtain enough pressure on the system to overcome osmotic pressure, and start producing freshwater. The spear valve can be closed up to the maximum allowed without reaching the unstable operation area for the wind turbine, as described previously in section 3. Therefore, the valve is closed until reaching the operating point in B (following the blue line in figure 4). The possible unfavourable effects of the transition between operating points A and B, i.e. water hammering, the sudden increase in the torque and decrease in rotational speed experienced by the rotor require further investigation..

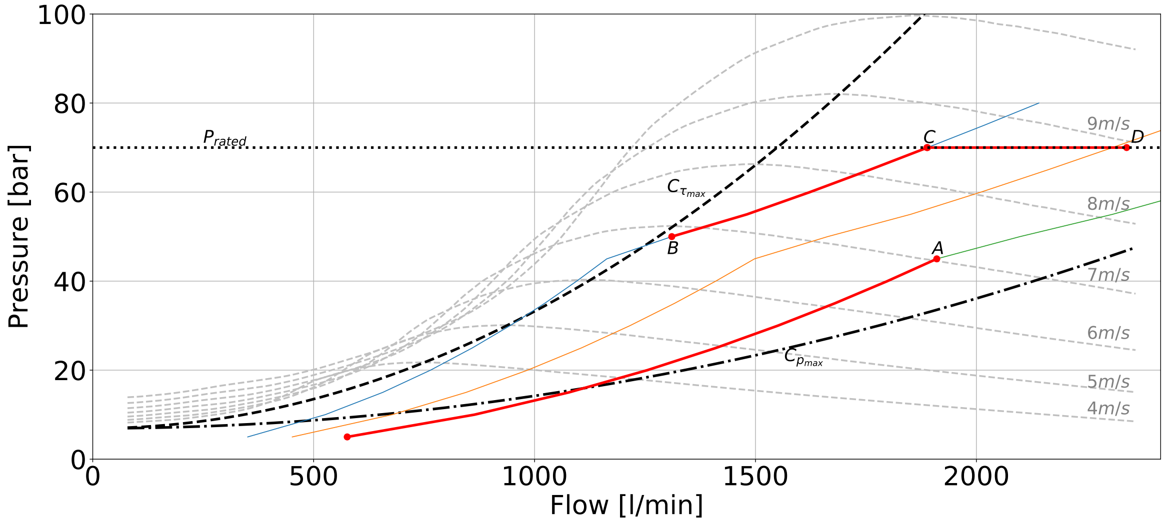

Figure 4: Turbine rotor and volumetric displacement pump pressure line curves at different wind speed U and fine pitch angle are represented in grey. The load (spear valve, SWRO desalination unit and ERD) is drawn for a fixed recovery rate and for different setting of the spear valve (small in blue, medium in orange and large in green). The proposed mapping of the operating settings follows the red line.

In the trait B-C, at higher wind speed corresponds to an increase in the high pressure pump seawater flowrate. Passive control is again implemented, with the spear valve position kept constant to the value set in B. The flow directed towards the SWRO unit is proportional to the driving force exerted on the membranes, as expressed by equation 8. The higher the wind speed, the higher the amount of water flowing towards the SWRO unit and the freshwater produced. The remaining flow is directed to the Pelton turbine for electricity production. It is important to notice that the ERD has a minimum flow that can be provided. Therefore, at the lower wind speed in the trait B-C, the recovery rate is lower that the desired one.

In point C, the pressure resulting from the current setting of the spear valve and the wind speed has reached the rated pressure of 70 bar. The rated pressure corresponds to the design operating pressure of the SWRO unit to obtain the required permeate flow. Therefore, the SWRO unit has reached maximum capacity and any excessive flow has to be deviated to the Pelton turbine.

From Point C to D, the spear valve is gradually opened to handle the increasing flow coming from the high pressure pump as the wind pseed increases. In this way, the water production subsystem keeps operating at rated flow and pressure. When the spear valve is fully opened and has reached the maximum flow that it can handle, or when the maximum rotational speed of the high pressure pump is reached, in D, pitch control is used to maintain the operational point.

The proposed strategy allows for an effective integration of electricity and freshwater production when the goal is to maximise the latter. The combination of active and passive control by means of the spear valve allows to safely produce water and electricity for a wider range of wind speeds, while the use of the ERD allows to maximise the water production for each operating point by increasing the recovery rate. In this configuration the electricity production is sufficient to cover the electricity consumption at any wind speed above 4 m/s. The option of doubling the capacity is made possible by doubling the number of pressure vessels.

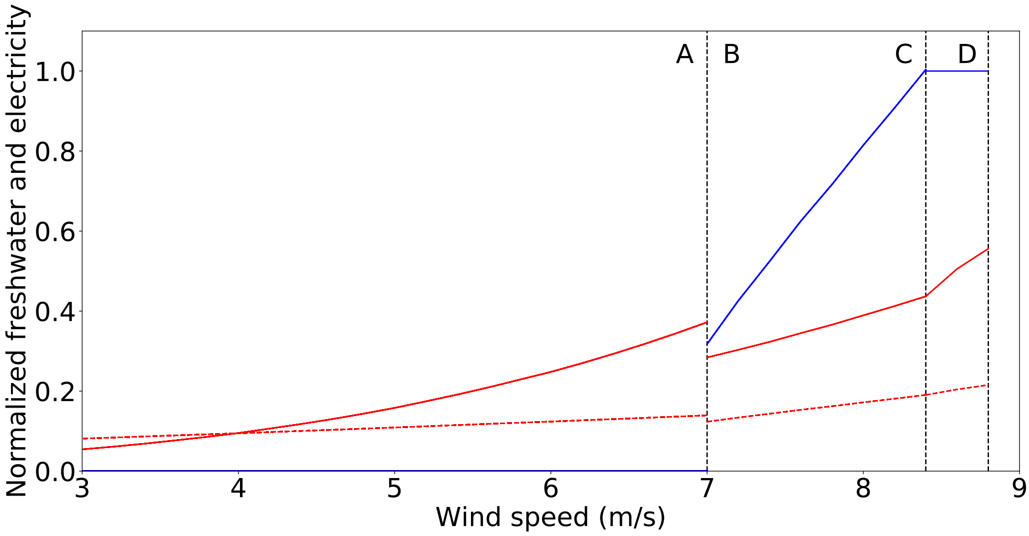

Figure 5: Freshwater production (in blue) and electricity production (solid red line) and consumption (dashed red line) at each wind speed as a result of the proposed control strategy

6. Conclusions

This paper presented the preliminary design of the application of the DOT hydraulic wind turbine for combined electricity and water production. A safe operation of the system is defined, taking into account the operational window of each component and their limits, especially the stringent constraints given by the reverse osmosis desalination unit. Within this safe operation envelope, a system of settings that allows the optimal performance of the system is obtained.

The philosophy behind the system settings can be summarised as follows: below osmotic pressure conditions, no water is sent to the desalination unit and all the flow is used for electricity production. As soon as water production can start, the settings are tuned to build up the pressure as fast as possible, and therefore reach the rated pressure. When rated pressure is reached, the settings are defined to let the desalination unit operate at constant operating point, while the electricity production increases until maximum flow rate or rotational speed is reached.

The next steps will be the translation of the hydraulic turbine and SWRO settings into the design and implementation of a robust control system.

Acknowledgement

The presented study is part of the DOT500kW Pilot Reverse Osmosis project, funded by the Demonstration Energy and climate Innovation, from the Netherlands Enterprise Agency. This research is supported by the Dutch Ministry of Economic Affairs and Climate Policy.

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