Experimental and Computational Study of a Wind Powered Reverse Osmosis System

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Challenge the future

Experimental and Computational Study of a Wind Powered Reverse Osmosis System

by

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Edoardo Bologna

Abstract

This project is based on the design of a hydraulic-wind-mill powered reverse osmosis (RO) desalination plant (Freshwatermill), focusing on increasing the energy efficiency of the system. While RO membranes are generally not designed for variable operation, wind energy has a characteristic unpredictability and variability. In particular, the project focuses on enabling the combination of RO and wind energy by finding a system configuration that will enable increasing the operating range in order to maximise the production of fresh water with the available wind energy without the use of energy storage. The proposed solution is to use the strategy of unit switching, in which multiple equally smaller RO membrane pressure vessel units can be switched on or off depending on the power supply in order to maintain the membranes within their optimal operating conditions of

As a first step, an experimental set-up is designed to test the behaviour of the RO system with a varying power supply and to measure how much fresh water production can be expected with the selected equipment depending on wind power. The test will then define whether the strategy of unit switching proves to be advantageous over a more traditional layout with a fixed numbers of units. After testing this strategy it is decided to reject it and opt for a fixed number of RO units as this is more advantageous in terms of fresh water quantity produced as well comprising a simpler and more robust RO system. Although the fixed RO system slightly lowers the fresh water quality at low powers, the level of salts remains within an acceptable range for drinking standards. Furthermore, with the fluctuating wind energy source, the lower quality water produced at low powers will combine higher quality water produced at higher powers resulting in an averaged out water quality in the long term.

In a second part a computer model will then be developed to carry out simulations on a complete Freshwatermill system (including the windmill and hydraulic drive-train) to test its performance as a whole. This allows determining the capacity of RO to couple to the hydraulic windmill in order to exploiting the full range of available wind power and maximise the fresh water production. A financial analysis is finally performed to evaluate whether increasing the RO capacity is worth the investment of additional components.

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Nomenclature

Symbols

Q	Volumetric flow rate
c	Concentratoin
γ	Recovery ratio
R	Rejection (salt)
J	Flux
A	Area
k_m	Mass-transfer coefficient
p	Pressure
π	Osmotic pressure
β	Concentration polarisation factor
Y	Average element recovery
n	number of elements in series
ω	rotational speed
τ	Torque
P	Power
r	Discount rate
$\overline{R}$	Ideal gas constant
$\overline{T}$	Maximum lifetime
I	Investment costs
M	Maintenance costs

λ	Tip-speed ratio
U	Wind speed
R_r	Rotor radius
C_p	Power coefficient
ρ	Air density

SUBSCRIPTS

f	Concentrate
p	Permeate
s	Surface
T	Temperature
$hydr$	Hydraulic
t	Time
sh	Shaft

ABBREVIATIONS

NDP	Net driving pressure
HPP	High pressure pump
ERD	Energy recovery device
PD	Positive displacement
TDS	Total dissolved solids
ROSA	Reverse Osmosis System Analysis
DWEER	Dual Work Exchanger Energy Recovery
HTB	Hydraulic turbo booster
ERI	Energy Recovery Inc.
LCoW	Levelised cost of water

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Introduction

Access to both drinking water and electricity is essential to ensure good living standards and inclusive, sustainable economic growth. They are fundamental resources for the reduction of widespread poverty. Yet, as of 2015 one tenth of the worlds population was still living without access to drinking water, one third without access to basic sanitation and almost one sixth of the population was without access to electricity [11, 12].

Many parts of the world rely on desalination to satisfy local water needs, whether for drinking, sanitation, agricultural or industrial purposes. Reverse Osmosis (RO) and electrodialysis are the most common desalination technologies that typically require electricity as an energy source. While they are more efficient than thermal desalination, remote water-scarce areas often lack access to electricity [13]. Diesel generators can alternatively be used to provide energy, although this would imply higher operating costs for the fuel itself and its transportation as well as maintenance costs.

In an effort to tackle this issue, the company Solteq Energy is developing the Freshwatermill, a technology that uses wind energy to power RO desalination and generates electricity with excess energy. The system is fully sustainable and thus independent from unreliable supplies of fossil fuels and their volatile prices. This makes it suitable for isolated and remote locations such as islands, river deltas, remote, coastal or small rural settlements as well as tourists resorts and golf courses. Essentially, it is applicable in any area with saline water resources, lacking access to affordable electricity and with an abundant wind energy resource.

1.1. Freshwatermill System Description and Development Status

The Freshwatermill is currently in its development stage with an operational pilot plant soon to be installed on the Colombian atoll of Johnny Cay, in the Caribbean. Solteq Energy intends to use second hand, refurbished Lagerwey 18/80 wind turbines, allowing to maintain low costs. However, the particularity and uniqueness of the system is that the windmill uses a hydraulic transmission; the nacelle doesn't contain a gearbox and generator but rather a gear pump which transmits the rotor's rotational power to a hydraulic fluid in a closed circuit. The high pressure fluid passes through two hydraulic motors on the ground which are coupled to an RO high pressure pump (HPP) and an electrical generator. The main flow of energy will be directed to the RO to produce fresh water, whilst the excess energy will be directed to the electrical generator.

By using a hydraulic transmission rather than converting the energy to electricity and back to rotational energy, as in a conventional wind turbine, it is expected that the conversion losses as well as friction losses of the gearbox transmission in the nacelle are reduced, allowing more power to be transmitted to the RO and generator on the ground. Furthermore, eliminating the gearbox gives the system more reliability. Gearboxes are the cause of up to 59% of turbine failures and thus the reason for a large part of their downtime, which has large economic consequences [14].

According to Ryan Williams and Paul Smith of Eaton Corporation [15], theoretically, there are several other aspects in favour of hydraulic transmissions in wind turbines. For instance, the nacelle would become considerably lighter than that of a traditional wind turbine as it would hold a pump which is much lighter than a gearbox and generator. This is because the power density of hydraulics are unmatched by other technologies. Consequently the tower design and foundation would be cheaper, not to mention cheaper and safer maintenance activities at ground level, as the necessity for costly, highly skilled technicians with climbing gear to work at the top of the tower is reduced. Hydraulics are in fact inherently far more reliable than electromechanical systems in extreme environments [15]. Virtually all the technology required for hydraulic drive-trains has been developed and improved over many years by the petroleum industry to operate in harsh conditions.

It is expected that the hydraulic pump would have a lower inertia than the mechanical components in a traditional nacelle, lowering the start-up wind speed and consequently widening the windmill's operational envelope. Overall, a hydraulic transmission would undoubtedly lower the life-cycle cost of a turbine [15]. The only obstacle to the adoption of hydraulic transmissions is that current off-the-shelf components are suitable for turbines rated up to 500 kW. This is due to the lack of investment on behalf of industries to develop and up-scale the hydraulic transmission technology until it becomes suitable for the low speeds and large size of megawatt-scale turbines.

The configuration of the technological concept that Solteq Energy has realised and from which it developed the pilot plant is shown in Figure 1.1. It shows in a wind turbine with a hydraulic transmission that delivers power to an RO HPP and an electrical generator. This is the basis from which to make improvements that will develop the system in a direction of high efficiency and reliability for use in its intended locations.

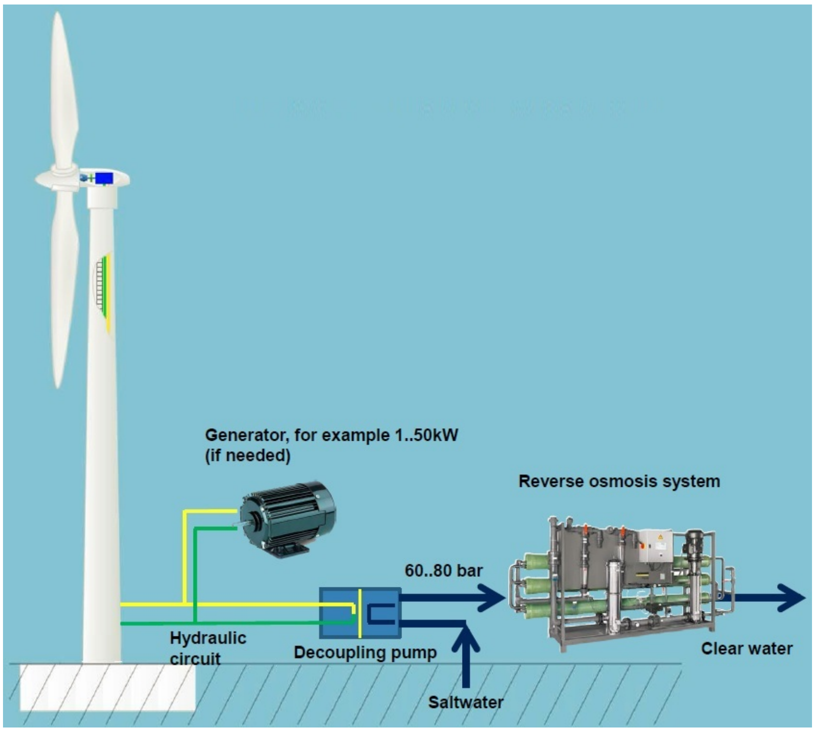


Figure 1.1: Freshwatermill configuration basis for pilot plant and future development [1].

Although the Freshwatermill may be produced on larger scale in the future, it is currently being developed for a nominal power of about 100 kW, for which efficient hydraulic components are available on the market - according to Solteq Energy it is anticipated this range of power, or more, can be obtained from a wind turbine rated with an electrical power of 80 kW if a hydraulic transmission is retrofitted. For this scale the maximum intended water production is around 400 m^3 of water a day as well as an additional 40 kW of electricity with excess energy.

1.2. PROBLEM DEFINITION AND PROPOSED SOLUTION

RO, like most other desalination technologies, is not suitable for variable power operation, making it problematic to be supplied by a fluctuating, intermittent renewable energy source such as wind. While the main flow of energy in the Freshwatermill will be directed to the RO, there are limitations on how much energy the RO can receive from the wind. In particular, the upper power limit is given by a maximum feed water pressure beyond which the membranes will be damaged [6]. On the other hand, if the power is too low, the feed pressure will not be sufficient to overcome the osmotic pressure and this will result in a low purity permeate. Moreover, HPPs, particularly the centrifugal type which are the most commonly used in the RO industry, become inefficient below their rated operational output. Similarly, RO membranes have certain flow and pressure condition ranges outside of which efficiency decreases [6]. More on the behaviour of pumps and membranes will be elaborated in Chapter 2, although it is for these reasons RO systems with spiral wound membranes are typically operated at constant flux rate and feed pressure, producing a constant flow rate of purified permeate [16]. Variable frequency motors and positive displacement pumps has been increasingly used to make the systems more efficient by giving them some more flexibility over the range of flows and pressures of operation to account for fluctuations in temperature and salinity of feed water as well as the deterioration of membranes due to fouling [7]. These pumps are nevertheless intended for relatively limited ranges - a membrane flux will typically reduce by about 20% in three years [16]. With an uncontrollable renewable energy source like the wind, however, the Freshwatermill's RO system will have to deal with much larger fluctuation, and the wider its operating range, the more wind energy it will be able to use.

It has long been suggested that potentially the cheapest means to deliver drinking water to remote locations without electricity access and adequate infrastructure is to use small renewable energy powered desalination systems [17]. Numerous desalination systems in fact already exist in which renewable energy is the main or only source of energy, many of which have proposed different solutions [6, 18]. Such plants require the integration of various systems which, even focusing on a renewable energy and desalination technology, leaves many options open to the possible combinations and layouts [6]. The intermittency and unpredictability of renewable energy remains a critical factor which limits the implementation of such energy sources with RO. This explains why in most cases they are used in combination with a constant power source or energy storage, allowing the RO to operate constantly, with the consequence of higher capital and operating costs [6]. Considering that the design of the Freshwatermill does not include either of these, it will have to be designed to best cope with the fluctuating nature of the wind.

The hydraulic transmission and RO system can be made of off-the-shelf components for a wind turbine rating of roughly 100 kW. This, beyond being more economical than producing specially made hydraulic pumps and motors, leaves little room for the improvement of the individual components. The transmission is being developed and tested externally to this project, although in parallel. This project will thus focus on the RO part, with the aim of finally combining data from the transmission test to model the full system. Therefore, the direction to follow for improving the efficiency is of finding a system strategy and or configuration that would allow expanding the operational envelope of the RO system to cope with the widest possible range of wind power and sizing the components accordingly - keeping in mind that an electrical generator will convert energy surplus beyond the RO's operation limits into electricity.

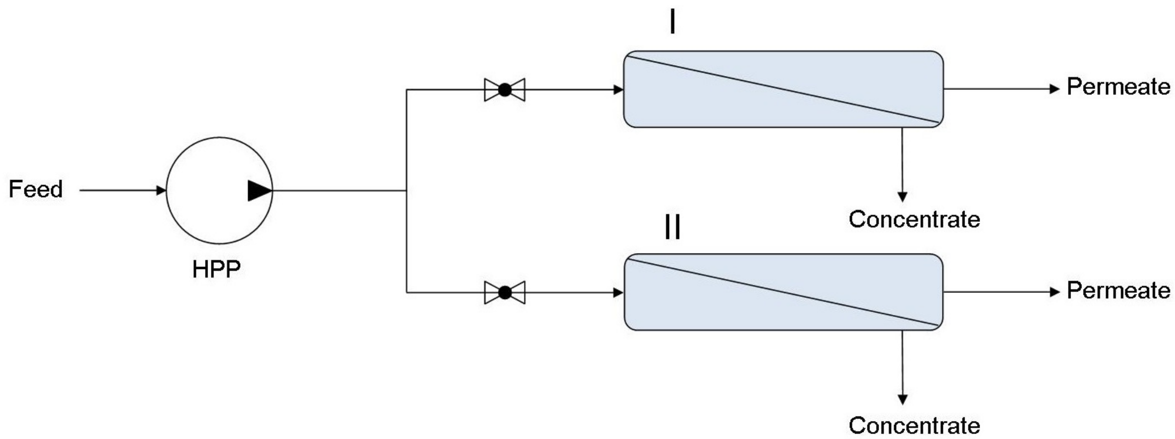


Figure 1.2: RO system with two RO units in parallel and valves able to vary number of active units depending on power.

The solution proposed in this thesis to widen the operating range of the RO system, allowing it to better cope with the fluctuating wind power supply, is that of using multiple equally smaller RO membrane-containing pressure vessels (or units) in parallel, as shown in Figure 1.2, that can be activated according to the power availability. At low power only one unit is operational, while additional units would be activated when the power increases and the single unit reaches its upper pressure limit. The advantages of this solution are that by managing the loads so that the demand more closely matches the generated power, the operation would be kept closer to optimal ranges where the desalination efficiency is high, while reaching a wider range of feed flow rates and pressures, thus usage of wind turbine power. Figure 1.3 shows an example of the expected power coverage ranges of two such units on a wind turbine's power curve, approximated using Reverse Osmosis System Analysis (ROSA); a software developed by DOW Chemical Company to calculate static performance parameters of the RO membranes it produces. It clearly shows how the range of power used by multiple units would be increased over a single unit. Furthermore, where the two areas overlap, either of the single or double unit layout are possible. In this power range, however, the single unit layout is closest to it's rated pressure limit therefore it would produce a permeate of higher purity than with two units.

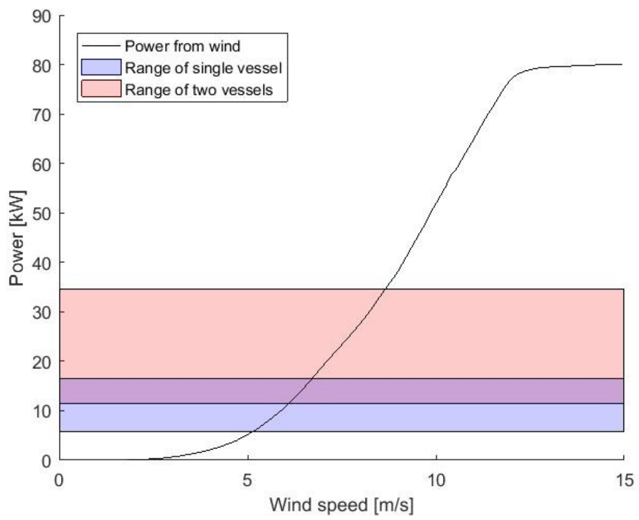


Figure 1.3: Wind turbine power curve with range of power usage for single and double RO units in parallel layout estimated with ROSA.

Without an auxiliary power supply or energy storage the RO units will nonetheless be subject to intermittent operation and after prolonged periods of inactivity at low wind speeds, flushing the membranes with permeate water is necessary. Until the wind power is sufficient to operate a single unit the flow can be alternated between the various units using valves, as showed in Figure 1.2, to reduce the frequency of flushing as well as the amount of fresh water used to flush them. On the other hand, frequent switching of membranes can cause damage to the membranes, shortening their life.

1.3. OBJECTIVE

This project is based on the development of a hydraulic-wind-mill-RO plant, focusing on the efficiency of the system in producing fresh water using the available energy. In particular, it focusses on enabling the combination of RO and wind energy by finding a system configuration that will enable increasing the operating range in order to maximise the production of fresh water with the available wind energy. The proposed solution is to use multiple equally smaller RO units which can be switched on or off depending on the power supply in order to maintain the membranes within their optimal operating conditions. This strategy will be examined to verify whether it gives a net advantage in terms of energy efficiency, permeate quality and cost. Successively the creation of a computer model will serve to perform simulations which allow to optimise the scale of the RO system to be coupled to the windmill.

The primary and secondary objectives of this thesis research can be summarised as follows:

Maximising the fresh water production of wind powered RO by configuring and sizing the system to widen its operational envelope.

1. *Test the behaviour of equipment selected to understand its production potential.*
2. *Verifying whether using an RO system with variable number of active RO units, depending on the power supply, will increase the range of wind power used, and thus permeate production, as well as maintaining high salt rejection.*
3. *Scaling the RO system in a computer simulation to make use of a larger range of power provided by the windmill and to test the system's performance in different operating conditions.*

1.4. APPROACH

This research project will comprise an initial technological review as well as a practical experiment and computer simulation model as means to reach the aforementioned objective. The technological review will set the grounds with the basic theory on RO and component selection. The experimental part will focus on the RO part of the Freshwatermill. It will serve as a practical test of the behaviour of the RO system with a varying power supply and to understand the potential of permeate production that can be expected depending on available wind power using the selected equipment. The test will also indicate whether the proposed solution of unit switching proves to be advantageous over a more traditional fixed membrane layout. The computer model will successively be developed to carry out simulations on a complete Freshwatermill system (including the windmill and hydraulic transmission) with an RO scaled for a power supply of about 100 kW, applying the proposed solution if it proves to be advantageous, and to test its behaviour in a dynamic simulation. Figure 1.4 shows the report structure including the main steps taken in each chapter.

The technological survey will provide the theoretical background on RO explaining the governing equations of flow through membranes. An overview will be made of RO combined with renewable energy sources, and on methods to tackle the issues of intermittency. A comparison of the main pumping technologies will be made in order to ultimately narrow down a selection of most promising RO pumps and, if needed, energy recovery devices for the Freshwatermill.

Preliminary sizing calculations will be performed to estimate the size of the components required to produce the amount of water desired from the system. The test set-up can therefore be designed and suitable components can be selected, depending on market availability.

The practical set-up will be built using the same RO pump and energy recovery that will form the desired finalised system. This makes the test important in giving an idea of the behaviour of the selected components and the performance of the whole RO system. The test should therefore include static measurements as well as a dynamic simulation with varying power in order to understand the system's response to the varying power supply and to measure the performance (or efficiency) of the system throughout the operating range.

Once the practical tests are concluded and the data has been processed to obtain the power usage of the system at different permeate flow rates for both single and double unit layouts, it can be decided whether having a system with varying number of units depending on power is beneficial. The computer simulation model of the complete Freshwatermill will successively be developed using Simulink. The model will first be verified with the practical test by simulating and comparing the same test results. Ideally, the model should include the power curve of the windmill and hydraulic transmission which is currently being measured in tests external to this project. The model can then be used to simulate operation with multiple RO system to evaluate whether it is beneficial to expand the RO capacity to the windmill's full potential, based on a financial comparison of different RO size configurations.

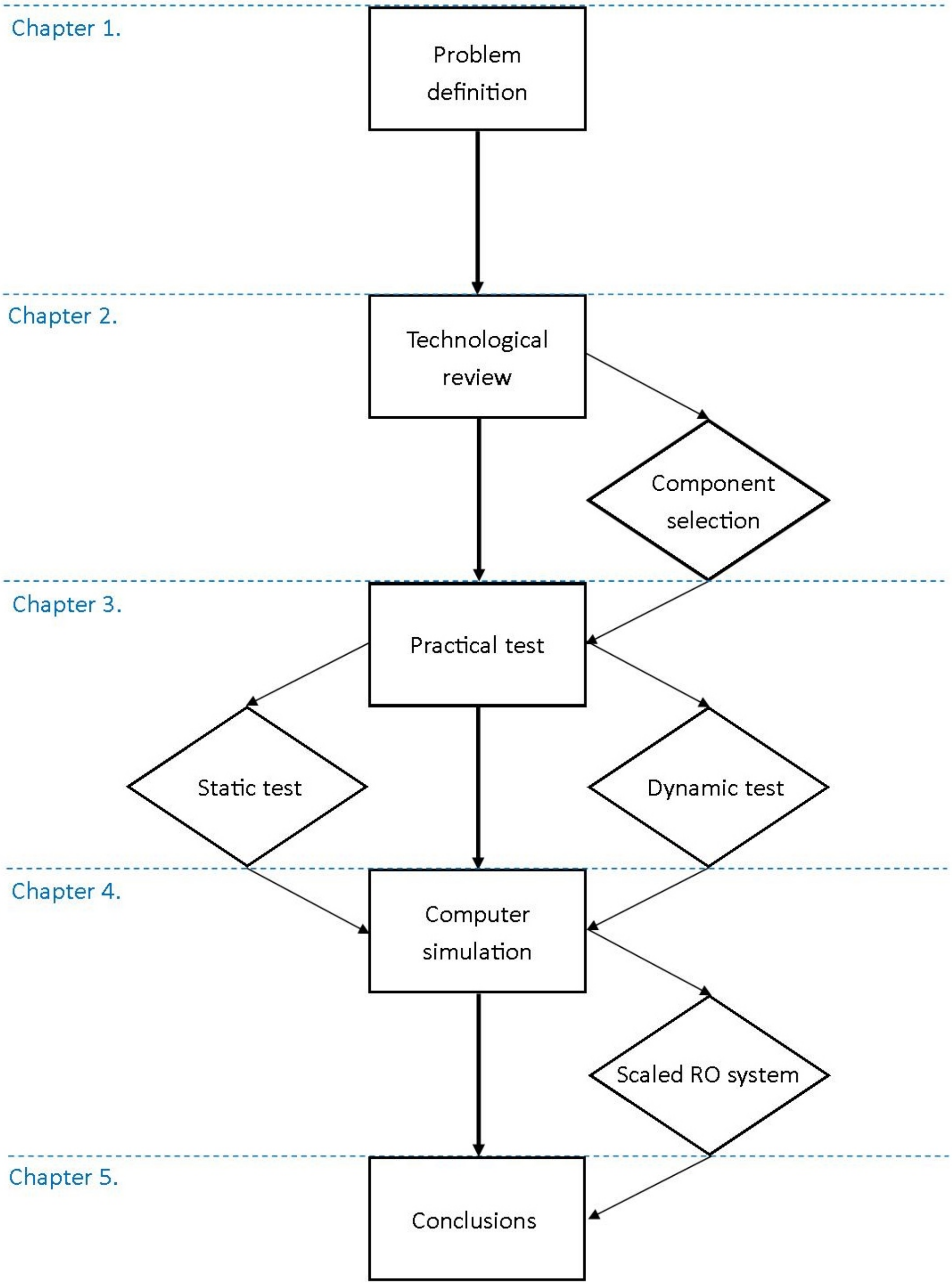


Figure 1.4: Flow diagram showing the structure of this report.

2

TECHNOLOGICAL REVIEW

The following chapter will give an overview of RO water desalination and its application in combination with the renewable wind energy source. It is important to understand and consider the limitations of RO in order to develop a stand-alone wind-RO system with high reliability and efficiency. The literature will bring to light the reasoning behind the proposed solution.

2.1. DESALINATION PROCESSES

There are numerous desalination technologies currently being applied in practice and others that are still being developed from the experimental phase. Membrane and thermal desalination technologies are the ones that have received the most commercial success so far with over 99% of the global desalination capacity [19]. The thermal processes that have been commercialised are multi-stage flash, multi-effect distillation and mechanical vapour compression. The most common membrane processes include RO, nanofiltration, electrodialysis, and electrodialysis reversal. RO has received substantial development in recent years and its lower energy consumption has allowed it to be even more widely accepted than the thermal alternatives reaching 62% of the entire desalination market [20]. RO is the fastest growing desalination market with more capacity being installed each year than any other technology [20].

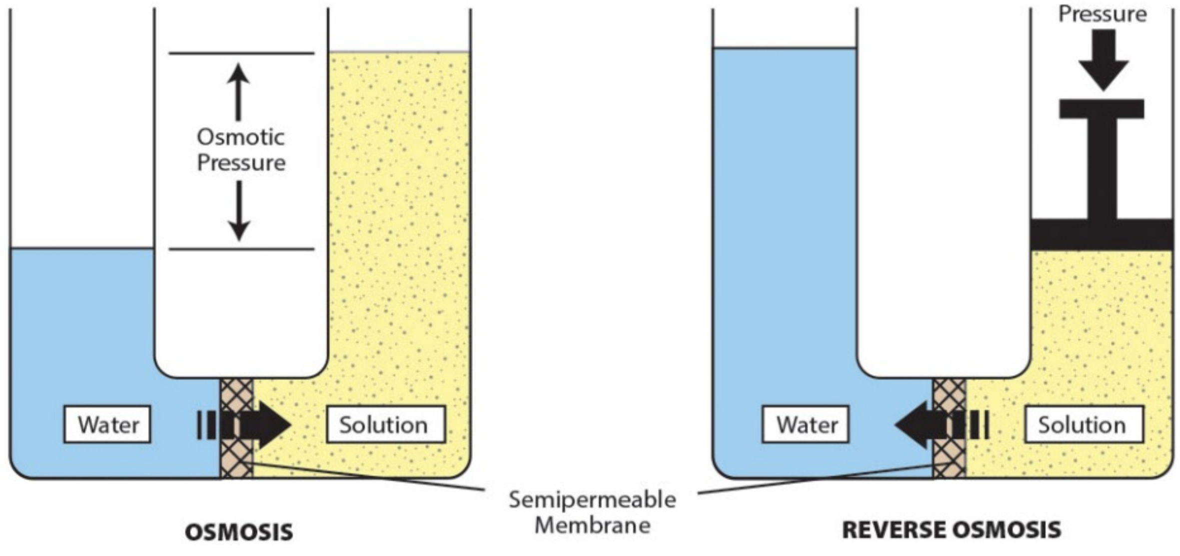


Figure 2.1: Principle of operation of osmosis and reverse osmosis [2].

RO membranes can desalinate brackish water, which ranges between 1000 and 30000 mg/l of total dissolved solids (TDS), and seawater, which has reaches up to around 45000 TDS, with very high salt rejection efficiencies of around 99%. TDS level represents the amount of mineral, salts, metals and ions dissolved in water. (The average seawater has about 35000 TDS). These membranes are also able to remove larger organic impurities, although smaller uncharged species may traverse the membrane. For drinking standards the World Health Organisation recommends an objective of up to 500 mg/l of TDS, although the palatability of drinking water with less than 600 mg/l TDS is considered to be good, while above 1000 mg/l becomes unpalatable [21].

2.2. PRINCIPLE OF RO

Reverse osmosis, as the name suggests, it is the opposite of osmosis. In osmosis, a solvent spontaneously moves, thanks to the naturally occurring osmotic pressure, through a semi-permeable membrane in the direction of the higher solute concentration, tending to equalise the concentration on either side of the membrane [2]. As shown in Figure 2.1, this process would continue until the pressure on the high solute concentration side equals the osmotic pressure. Therefore, RO is the process by which a solvent is de-mineralised or de-ionised as it is forced through a semi-permeable membrane by applying a pressure to it which overcomes the osmotic pressure [2].

In practice RO desalination works by pumping high pressure salt water though a semi-permeable membrane. This increases the pressure on the salt side of the membrane. The water molecules are pushed through the membrane to form a pure water permeate stream, leaving behind the salt molecules which form a concentrate stream of brine containing around 95-99% of dissolved salts or other contaminants. The common RO water desalination process using spiral wound membranes is applied as cross-flow filtration as shown in Figure 2.2. This schematic diagram shows the feed water being pumped into an RO membrane and separated into a pure permeate stream at low pressure and a concentrate stream at high pressure. The pretreatment is required to remove suspended solids among other things and can help to reduce the work required for the HPP [2].

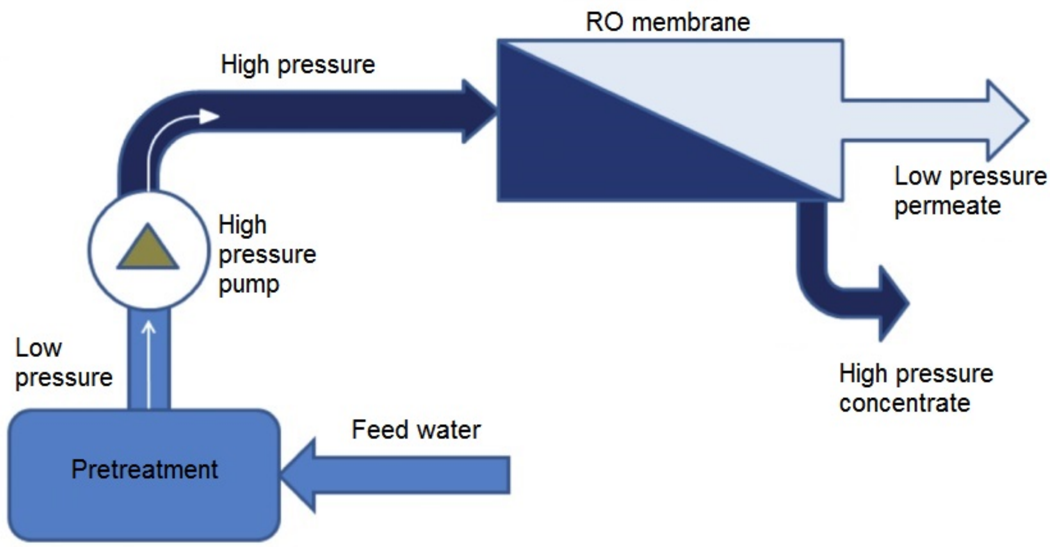


Figure 2.2: Schematic diagram of desalination process [3].

Taking a closer look at the cross-flow process of spiral wound membranes shown in Figure 2.3 it can be seen that the membranes are in form of a flat sleeve (green) wound spirally around a central pipe. The sleeves are sealed on all outer edges but open to the edge connected to the central pipe. The membrane element would be contained in a high-pressure vessel, often with several other membranes, to increase surface area, packed and sealed end-to-end in series, forming an RO unit. Pressurised salt water (red) flows along the axis of the cylinder, between the spirals, along the outside of the sleeves which are kept separate by apt porous spacers which induces turbulence. Part of the water will seep though the membrane leaving behind the salt. The water that penetrates the membrane is the desalinated permeate (blue) and makes its way though the sleeve, which is also supported by a porous spacer to keep the sleeve from collapsing under osmotic pressure, towards the central pipe where it is collected and flows out of the vessel.

The rapid cross-flow of salt water along the external side of the membrane sleeves helps to remove the locally higher concentration of salt accumulated on the membrane surface which has been left behind by the permeate. This phenomenon, known as concentration polarisation, would otherwise hinder the passage of additional water through the membrane. A lower recovery, or fraction of permeate to feed water, would decrease the concentration polarisation as turbulence of the flow would decrease. For this reason operating with a feed water flow rate for extended periods of time can be problematic.

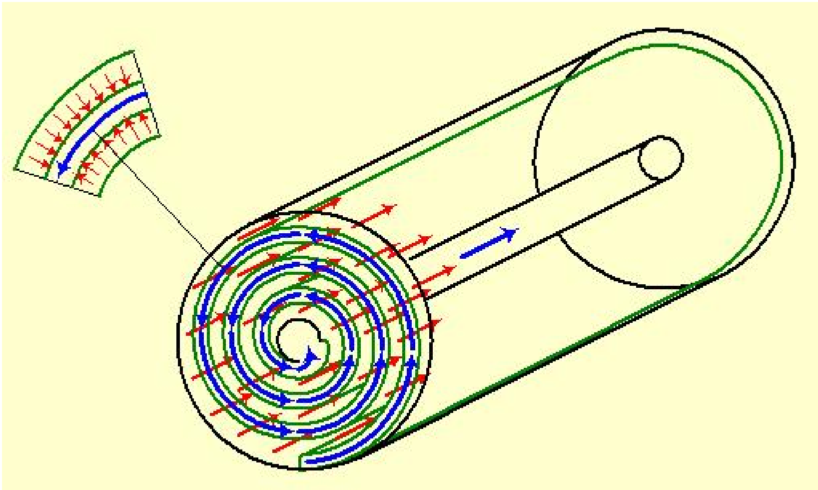


Figure 2.3: Spiral wound membrane and cross-flow filtration [4].

2.2.1. EFFICIENCY OF RO

The efficiency of RO desalination is measured in terms of specific energy consumption. That is the minimum energy used per unit volume of permeate water produced in kWh/m^3. Theoretically, the minimum energy for the desalination of seawater with 35000 mg/l is 0.76 kWh/m^3 for 0% recovery and 1.6 kWh/m^3 for 50% recovery, although the lowest reported energy consumption for RO is about 2 kWh/m^3 [22].

2.2.2. FUNDAMENTAL EQUATIONS

The following section will provide the main equations that describe the RO membrane filtration process.

MASS BALANCE

The balance for water across a membrane element is given in equation 2.1.

$$Q_f = Q_c + Q_p \tag{2.1}$$

Where Q_f, Q_c and Q_p are feed, concentrate and permeate flow rates, respectively, in m^3/h.

Including the concentration of dissolved solids, the mass balance is as follows:

$$Q_f c_f = Q_c c_c + Q_p c_p \tag{2.2}$$

In equation 2.2 c_f, c_c and c_p are feed, concentrate and permeate dissolved solids concentration, respectively, in g/m^3.

The recovery (γ) is defined as the percentage of permeate flow rate extracted from a membrane to the total feed flow, as in equation 2.3.

$$\gamma = \frac{Q_c}{Q_f} 100\% \tag{2.3}$$

The rejection (R) described the percentage of TDS rejected by a membrane and is calculated in equation 2.4.

$$R = \frac{c_f - c_p}{c_f} 100\% \tag{2.4}$$

KINETICS

The equations governing the kinetics of RO membrane filtration are provided below [23] [24].

The permeate flow rate per unit area of membrane is called the flux (equation 2.5).

$$J = Q_p / A_s \tag{2.5}$$

Where J is the flux in $m^3/m^2 s$, Q_p is the permeate flow rate in m^3/s and A_s is the total surface area of the membrane system in m^2.

The flux can also be calculated as in equation 2.6.

$$J = k_m * NDP \tag{2.6}$$

Where k_m is the membrane permeability coefficient, or mass-transfer coefficient, in s/kg and NDP is the net driving pressure in Pa. Equation 2.6 is valid for 25 °C. Deviating from this temperature would have an effect on the flux, requiring a temperature correction factor (TCF) shown in equation 2.7.

$$J_T = J_{25} 1.03^{(T-25)} \tag{2.7}$$

Where J_T is the flux at a specific temperature T in °C and J_{25} is the flux at 25 °C.

The NDP is the hydraulic driving force across the membrane minus the net osmotic back pressure, as shown below.

$$NDP = \Delta p - \Delta\pi \tag{2.8}$$

Where Δp is the transmembrane pressure (TMP) and $\Delta\pi$ is the osmotic pressure difference in Pa.

For cross-flow membrane filtration the TMP is defined as the difference in pressure between the average feed-concentrate side and the permeate side of the membrane and can be calculated as in equation 2.9. It describes the hydraulic driving force for permeate flux to occur. The pressure is averaged over the membrane, therefore, it is independent of position along the membrane.

$$\Delta p = \frac{p_f + p_c}{2} - p_p \tag{2.9}$$

Where p_f is the feed pressure, p_c is the concentrate pressure and p_p is the permeate pressure, all in Pa.

The TMP can be rewritten as follows:

$$\Delta p = p_f - \frac{\Delta p_{hydr}}{2} - p_p \tag{2.10}$$

Where p_{hydr} is the hydraulic pressure loss on the feed-concentrate side, caused primarily by the high pressure flow though the porous spacer. This can be described as follows:

$$\Delta p_{hydr} = p_f - p_c \tag{2.11}$$

The osmotic pressure difference, similarly to the TMP, is the difference in osmotic pressure between the average feed-concentrate side and the permeate side of the membrane and can be calculated as in equation 2.12. The osmotic pressure difference is also averaged over the membrane, making it is independent of position along the membrane.

$$\Delta\pi = \frac{\pi_f + \pi_c}{2} - \pi_p \tag{2.12}$$

The concentration of dissolved solids in the permeate is often left out because it becomes so low that it can be considered negligible.

N.B. NDP and TMP are sometimes mistakenly interchanged or misused in literature although the above definitions are the most widely accepted.

CONCENTRATION POLARISATION

As water is filtered through the membranes a build up of dissolved salts will occur on the boundary layer of the feed-concentrate side of the membrane. This effect, called concentration polarisation, will cause a reduction in flux which can be minimised by creating turbulence in the boundary layer. During operation the concentration polarisation will affect the feed-concentrate average osmotic pressure. A concentration polarisation factor (β), is used to account for this. β can be estimated using equation 2.13. This factor is taken into account by multiplying it with the feed-concentrate average osmotic pressure.

$$\beta = e^{0.7Y} \tag{2.13}$$

Where Y is the average element recovery given by the following equation:

$$Y = 1 - (1 - Y)^{1/n} \tag{2.14}$$

n is the number of elements in series.

2.2.3. FACTORS AFFECTING RO PERFORMANCE

The performance of RO is affected by various factors that are related with one another. An overview of some of these factors, including temperature, pressure, feed water salt concentration and permeate recovery, is given below. These variables have an effect on the energy requirement of the process and the permeate water quality.

The minimum pressure required for the feed water is the osmotic pressure. This depends on the salt type and concentration and the temperature of the feed water, as explained by van t'Hoff's law [25]:

$$\pi = c\overline{R}T \tag{2.15}$$

where π is the osmotic pressure, c is the solute concentration in mol/l, $\overline{R}$ is the ideal gas constant $J/molK$ and T is temperature in K. Therefore, the higher the salt concentration or temperature of the feed water, the higher the osmotic pressure to be overcome. Figure 2.4 (a) shows that, assuming constant feed water pressure, increasing its salt concentration (by reducing salt rejection) will reduce the permeate flux. The feed water pressure will be offset by the increasing osmotic pressure. The salt rejection from the feed water will also decrease as the permeate flux is reduced.

Temperature has a larger affect on the overall performance. Assuming the pressure of the feed water is maintained constant, an increase in feed water temperature will result in a higher permeate flux through the membrane [5]. This relation is almost linear as can be seen in Figure 2.4 (d) and is mostly due to the increase in diffusion rate of the water molecules through the membrane. As a rule of thumb, one degree centigrade results in a 3 % change of permeate flux. An increase in feed water temperature will also result in a slightly lower salt rejection, or higher salt passage through the membrane, reducing the purity of the permeate. This is also due to the higher diffusion of salt molecules through the membrane.

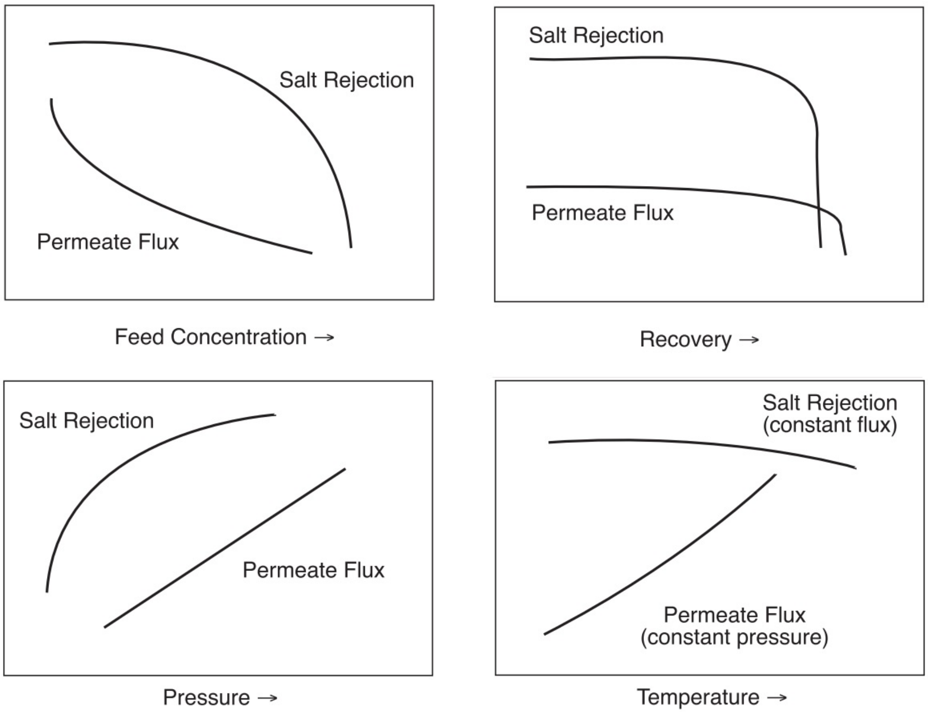


Figure 2.4: (a) Effect of concentration (top left), (b) recovery (top right), (c) pressure (bottom left) and (d) temperature (bottom right) on permeate flux and salt rejection [5].

Figure 2.4 (c) also shows that permeate flux increases linearly with increasing feed water pressure. Salt rejection also increases with feed water pressure, although non-linearly. RO membranes are not perfect barriers, therefore there will always be some passage of dissolved salts. The salt passage is increasingly reduced with increasing feed water pressure as the water molecules are transported through the membrane at a faster rate than salt molecules. The salt rejection eventually reaches a plateau as there is a limit to the salt that can be rejected with increasing feed water pressure. The salt will eventually remain coupled with the water permeating the membrane.

The permeate recovery also affects the permeate flux and salt rejection. RO requires a feed water pressure that can overcome the osmotic pressure and reverse the naturally occurring osmotic flow. If the permeate recovery is increased, more salts will be left behind in the concentrate stream which will increase the osmotic pressure until it is equal to the applied feed pressure. As shown in Figure 2.4 (b), this would slow or stop the feed flow completely reducing the permeate flux and thus salt recovery to zero.

The maximum recovery ratio usually doesn't depend on the limiting osmotic pressure but rather on the concentration of salts in the feed water as well as their tendency to precipitate on the membrane causing mineral scaling. Mineral scale often include calcium carbonate (limestone), calcium sulphate (gypsum), and silica. This can be inhibited by chemical treatment of the feed water.

The optimal recovery ratio depends on the relative cost of the feed water pretreatment and of desalination, both of which will vary under different conditions. A high recovery will save on the cost of pretreatment whereas a low recovery will favour a lower desalination cost [4].

2.3. RO WITH RENEWABLE ENERGY

The combination of RO with renewable energy, particularly the more established wind and solar sources, has been discussed and studied extensively with several operational plants existing since the mid 1980s [6, 17, 18, 20, 26].

Wind power is the most used renewable source in combination with desalination plants and it is mostly used with an auxiliary energy supply, whether within a hybrid system with diesel power or in a grid connected system [27].

For a stand-alone system without alternative energy supplies or energy storage, like the Freshwatermill, intermittent operation is therefore inevitable and at low wind speeds it is bound to arrest.

2.3.1. INTERMITTENCY

The recurring limiting factor for the operation of RO with renewables is the intermittency of such sources. Variable power is typically not suitable for RO operation [6]. Despite recent progress in the development of membrane technology that brought about higher tolerance to pressure fluctuations and improved rejection rates, it remains important to operate between certain pressure and flux ranges in order to obtain high efficiencies.

A RO operational window established by Feron (as cited in [6]) which contributes to the application of wind powered systems is presented below (see Figure 2.5). It concerns the feed flow and pressure ranges within which RO membranes can aptly operate.

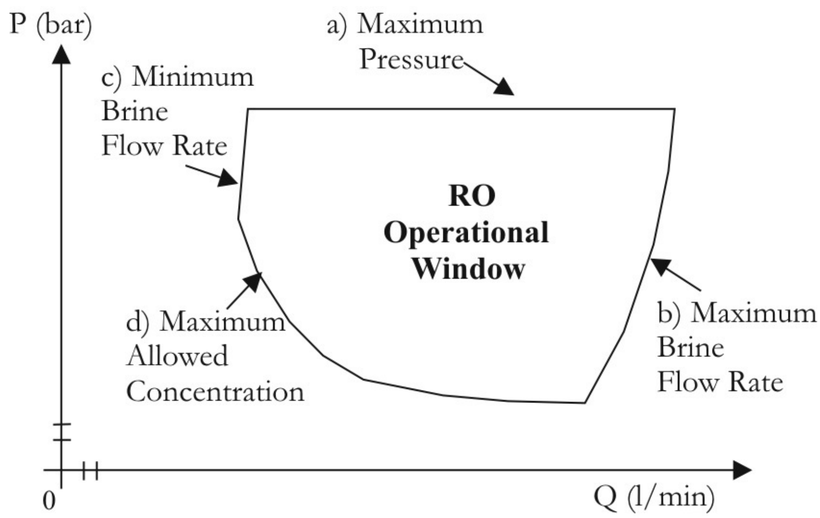


Figure 2.5: RO membrane pressure and flow rate operational window [6].

The operational window is contained by four limits.

Maximum feed pressure This is a physical limitation of the membrane determined by its mechanical resistance;

Maximum brine flow rate Membranes can deteriorate if this limit is reached;

Minimum brine flow rate Going beyond this limit would cause precipitation on the membranes which would consequently lead to fouling;

Maximum product concentration The permeate concentration will increase to levels above acceptable drinking water standards if the feed pressure is not high enough.

2.3.2. Configuration Possibilities of Wind-RO Systems

Based on a research carried out by Miranda et al. [28], a description of the various configurations or techniques that can be applied to combine wind energy and RO is presented.

System with Diesel or Grid Back-Up

To ensure that the RO runs constantly, the wind energy can be backed-up by either a diesel generator or connection to the local electrical grid. This type of solution would considerably lower the running cost by saving on fuel or electrical energy. On the downside, interruptions of the supplementary power supplies due to power cuts or diesel generator maintenance may cut the RO operation completely as it would not be designed to operate at partial load.

When no supplementary energy source is used, the possibilities can be further divided between RO systems that operate almost constantly and ones that vary their production according to the wind power. For constant operation the methods are using energy storage, switching RO units on or off and de-rating the wind turbine. For variable operation a control strategy can be determined to make use of the operational window defined by Feron [28].

Energy Storage

Storage devices such as batteries can be used to accumulate excess energy in periods of high wind speed, in which the power generated is above the rated power of the RO, to be used in moments when the energy supply is insufficient with respect to demand. Batteries can be used to store energy, although at high powers ratings these can make the system economically unattractive. The use of batteries also adds complexity to the system, which is something unwanted when operating in a remote area. Batteries also entail an electrical energy supply from the wind turbine, although compressed air energy storage can also be used for mechanical or hydraulic power transmission.

De-Rating Wind Turbine

This involves lowering the rated power of a wind turbine so that a larger part of the power curve will provide constant power output. This may require using turbines with a much higher original rating than required for the RO, which will increase costs, although the rated wind speed will be much lower, thus widening the range of constant operation of the turbine. This can be done using active pitch control, therefore only such turbines that use this mechanism can be used.

Switching RO Units

In this strategy the turbine supplies power to multiple small RO pressure vessel units in parallel configuration. Each unit can be switched on or off depending on the power availability from the turbine to try and obtain relatively constant pressure and flow conditions on each unit. This method can be used on scales of several hundred kilowatts. On the downside, frequent switching of membranes has been shown to shorten their lifetime. To reduce the switching frequency, a study has combined pitch control and a short term energy storage (flywheel) device to smooth out the fluctuations [29]. Another solution is to use additional loads to absorb power and keep the operation more constant.

VARIABLE OPERATION CONTROL STRATEGY

To operate an RO system under varying conditions, a control strategy can be created which sets a specific pressure and flow rate, remaining within the operational limits described by Feron, based on a power input (the product of pressure and flow rate is power). This should enable autonomous operation over a wider range of power without the need of auxiliary back-up power or storage. The capital and operating cost of such a system would be reduced. The effects of variable operation on membranes are not fully known, although it is expected that membrane lifetime can be shortened due to mechanical fatigue.

VARIABLE RECOVERY RATIO

To add to the topic of operating RO under variable conditions, a study performed at the Centre for Renewable Energy Systems Technology (CREST), at the university of Loughborough, has shown that varying the recovery ratio according to the operating conditions is critical in improving the efficiency of a system without storage or auxiliary power [7]. However, this cannot be done with the use of positive displacement HPP-ERD devices such as Clark pumps or hydraulic pump-motor assemblies alone (these devices will be described in section 2.5). The optimum recovery ratio is not only dependent on power but also on feed water temperature and concentration as well as membrane conditions. Figure 2.6 shows the regions of optimum recovery ratio over a range of power only considering the effect of varying feed water temperature.

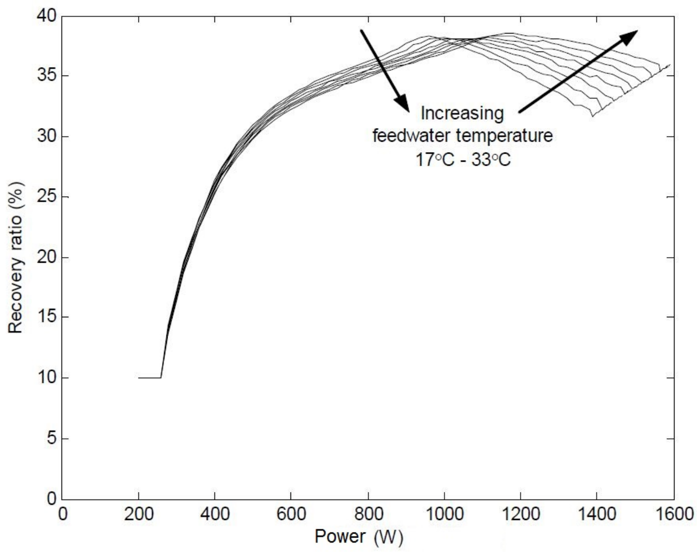


Figure 2.6: Points of optimum recovery ratio vs. available power, considering variations of feed water temperature [7].

2.3.3. SIZE AND NUMBER OF MEMBRANE ELEMENTS

Feed flow rate and pressure have a direct effect on the specific energy consumption for desalination (kWh/m^3). Conventional grid-connected RO systems generally operate at given flow and pressure conditions which will maximise the permeate production out of the installed membrane area [7]. While this will keep the capital cost low, the operating cost may be higher than it could be. For a renewable energy-powered system, where efficiency may be more important, reducing the feed flow and pressure will substantially lower the specific energy. The reduction of permeate flow that would also occur can be compensated by increasing the membrane area. A drawback is that lower feed pressure will also increase the permeate's salinity, and temperature will also be a factor [28].

2.4. HIGH PRESSURE PUMP

The HPP is a fundamental component of an RO system. In a system such as the Freshwatermill where pumping power is delivered though fluctuating wind speed, it is especially important to select an appropriate pump that can efficiently cope with this type of operation. The following section gives an insight into the types of pump available and the rationale for selecting a suitable one for the Freshwatermill.

2.4.1. TYPES AND CHARACTERISTICS OF PUMPS

There are two main types of pumps: the positive displacement (PD) type and kinetic pumps, of which the centrifugal type is the most common. The two types of pumps have different operating characteristics. Analogously to electrical systems in which there are current and voltage sources, in general terms, PD pumps are sources of flow whereas centrifugal pumps are sources of pressure [30].

PD pumps create flow by transferring packages of fluid from a suction port to a discharge port where it is released. Pressure can result from such a system in response to the defined flow rate. If the discharge port was to be left unconnected then the fluid flow would exit at atmospheric pressure. The flow rate is directly proportional to the displacement volume of the pump, thus also linearly related to its rotational speed. PD pumps work well to deliver near to constant flow rates against high pressures.

Centrifugal pumps create pressure using an impeller to accelerate the fluid before converting its velocity to pressure in a specially shaped funnel called volute. The fluid would be discharged at the pressure developed in the volute if the discharge port were to be left unconnected. Flow would occur as a result of the pressure if it were to be connected in a system.

Figure 2.7 (a) shows the performance of PD and centrifugal pumps. It clearly shows that a PD pump can deliver a constant flow rate independently of pressure head, while centrifugal pumps flow rate will vary greatly with a small change in pressure.

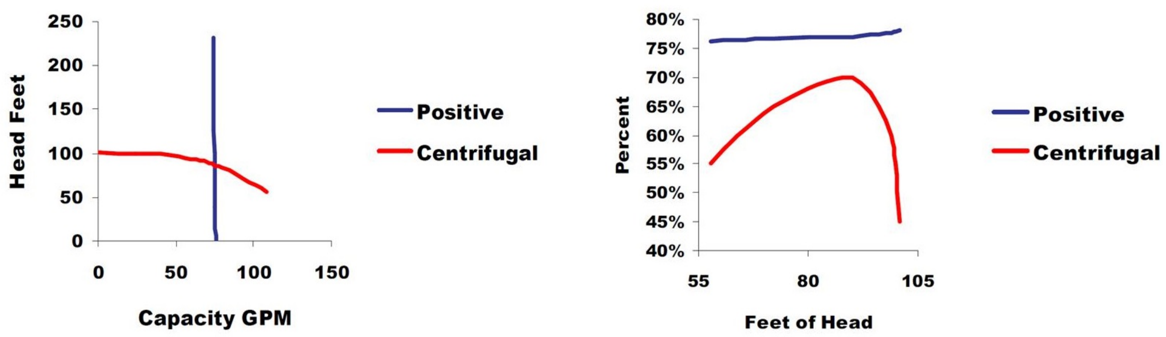


Figure 2.7: Graphs comparing (a) performance (left) and (b) efficiency vs. pressure head (right) of PD and centrifugal pumps [8].

Another important difference between PD and centrifugal pumps which will influence the selection of pump for the Freshwatermill is their difference in mechanical efficiencies when operating at different pressures. Looking at Figure 2.7 (b) we can see that PD pump efficiencies remain high and nearly constant against a full range of pressure heads, while centrifugal pumps only peak at a certain pressure head at which they have been designed to operate. This alone demonstrates the larger flexibility of PD pumps at varying operating conditions.

PUMP SELECTION

In commercial RO plants, the most used feed HPPs are the centrifugal multi-stage type. This is because the plant operation is generally constant. The permeate flux of membranes typically reduce by about 20% over a three year period due to their deterioration, therefore, to maintain constant operation, centrifugal pumps are often oversized in order to make up for this deterioration [16]. The feed pressure is thus regulated by throttling the flow with a feed valve which entails significant losses which reduces the system efficiency. Variable frequency drives are becoming more frequent as a measure to regulate the feed pump flow and pressure over wider ranges with low efficiency reduction. For the purpose of operation flexibility, even better is to use PD pumps which enable variations of pressure or flow output with a very small change in efficiency. The capacity limitations and higher maintenance requirements make them less common [16]. As for all other components in an RO system, the material constituting the pump should be resistant to seawater corrosion.

For the application of a stand-alone wind powered RO systems, operational flexibility is highly desired to make use of as wide possible a range of wind powers. A PD HPP would thus be more suitable than a centrifugal pump as it would more efficiently deal with fluctuating power from the wind.

2.5. ENERGY RECOVERY DEVICE

In seawater desalination the recovery ratio is low in comparison to brackish water desalination. There is a high flow rate of high pressure brine which contains a considerable fraction of the energy supplied to the feed stream - the pressure only drops minimally from feed to concentrate due to turbulence losses while flowing through the porous spacers. Energy recovery devices (ERD) can be used to recover part of this energy and direct it back to the HPP. ERD can have a substantial effect on the efficiency of RO. With ERDs the capital cost of a desalination plant will increase but the running costs are reduced significantly because of higher efficiencies [31]. Some types of ERD are able to reduce the SEC to between 2-3 kWh/m^3 [32]. When considering a stand-alone wind powered system such as the Freshwatermill which aims to maximise the permeate production, an ERD may be beneficial to improve the efficiency.

Different types of ERD are available, some of which are more suitable for mid- to large-scale RO systems, namely Pelton wheels, turbo chargers, DWEER work exchangers and ERI pressure exchangers, and others, such as Clark pumps and hydraulic pumps, which are more suitable for small-scale systems which produce less than 50 m^3/d [9]. At about 400 m^3/d, the Freshwatermill can be considered a mid-scale RO plant. However, the fact that it will operate over a wide range of power supply further complicates the choice of ERD.

2.5.1. ERDS FOR MID- TO LARGE-SCALE RO

A description of the main types of ERDs for mid- to large-scale RO plants is given below [31].

PELTON WHEEL

Pelton turbines (Figure 2.8 (a)) connected directly to the drive shaft of the high pressure pump provide a well proven, reliable energy recovery. The efficiency is, however, only modest. Pelton wheels are designed for a specific flow rate and pressure, making it more suitable for the conditions in hydroelectric plants. They are not suitable for variable operation as their efficiency rapidly drops away from their design conditions.

TURBO CHARGER

The turbo charger (Figure 2.8 (b)), also called hydraulic pressure booster (HPB) or hydraulic turbo booster (HTB), works by recovering the concentrate stream energy in radial inflow turbine and transmitting the power via shaft to a centrifugal pump on the feed line, downstream of the HPP. It therefore works independently of the HPP, allowing it to operate at more efficient regimes that a Pelton turbine which is dependent on the HPP motor speed. With specific control valves, it can be used to regulate feed pressure.

DWEER

Dual Work Exchanger Energy Recovery (DWEER) devices transfer hydraulic pressure energy in the concentrate stream directly to hydraulic pressure energy in the feed stream without the mechanical conversion via shaft such as in Pelton wheels and turbo chargers, making it more efficient. The DWEER system is made of two cylinders, each of which contains a free piston. As high pressure concentrate water flows into one side of a piston, feed water is pressurised on the other side. In the second cylinder low pressure feed pushes the piston to displace concentrate which has already lost its pressure. The role of the two cylinders is alternated by automatic valves allowing a continuous process. As shown in Figure 2.8 (c) only part of the feed is directed to the DWEER to be pressurised, the other part goes directly to the HPP. The part which is pressurised then joins the high pressure feed, downstream of the HPP, although a small booster pump is required to compensate the pressure loss by the concentrate in the membrane and in DWEER system. This pump would be impractical for the Freshwatermill as it would require additional power to be sourced from the hydraulic transmission.

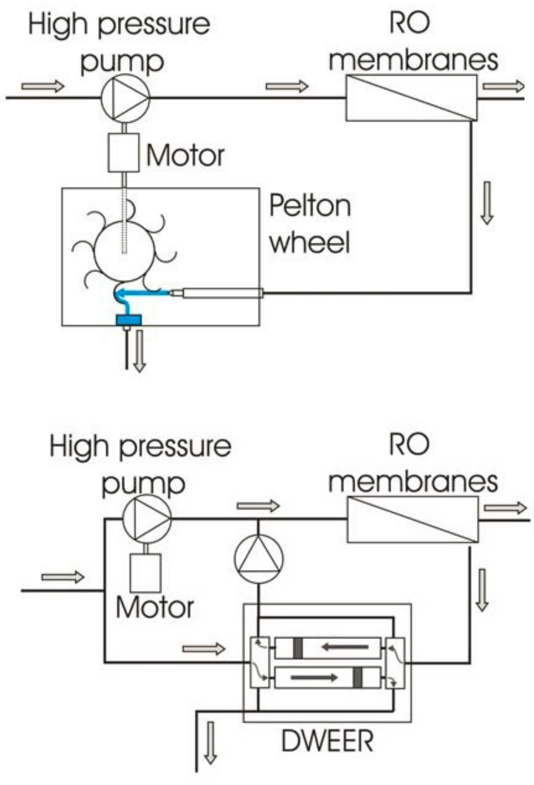


Figure 2.8: Energy recovery via (a) Pelton wheel (top left), (b) turbo charger (top right), (c) DWEER (bottom left) and (d) ERI pressure exchanger (bottom right) [9].

ERI PRESSURE EXCHANGER

Similarly to the DWEER, the Energy Recovery Inc. (ERI) pressure exchanger (Figure 2.8 (d)) transfers work from the high pressure concentrate to the low pressure feed, although it has multiple cylinders in a revolving magazine and the concentrate and feed come into contact with each other as there is no piston. This means that there is slight mixing between the two streams although the increase in salinity of the feed stream is only minimal. The magazine rotation is actuated by the flow of water itself and needs to be carefully regulated to ensure low levels of mixing. As in the DWEER, the ERI pressure exchanger only sources part of the feed stream; the rest goes to the HPP. This type of configuration requires regulation of the streams to ensure the right proportions are achieved. With a varying power supply, such as in the Freshwatermill, this more complex configuration would be more difficult to continually regulate, making it somewhat less practical. Furthermore, the operational ranges of ERI pressure exchangers are rather limited and would not be able to operate over a full range of wind power from the Freshwatermill.

2.5.2. ERDS FOR SMALL-SCALE RO

Many small-scale RO systems are designed without ERD to keep the capital cost low. When they do include an ERD, a positive displacement is far more efficient at this scale. Both DWEER and ERI pressure exchanger are classified as positive displacement systems although neither of these are produced on small-scale. Literature shows that both Clark pumps and axial-piston pumps can provide efficient energy recovery for small-scale RO systems [31] [7] [9].

CLARK PUMP

The Clark pump (Figure 2.9 (a)) is similar to the DWEER device although instead of having two independent cylinders there is a rod that connects two pistons in two in-line cylinders. High pressure concentrate fills the back- or rod-side of a cylinder while pressurising feed water on the other side of the same piston. In the

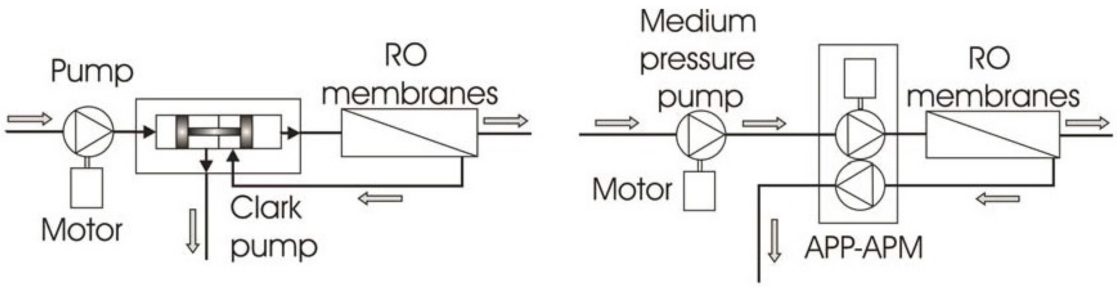


Figure 2.9: Energ recovery via (a) Clark pump (left) (b) and hydraulic motor (right) [9].

opposite cylinder, feed water will fill the front of the cylinder while exhaust, low pressure concentrate will leave the rod-side of the same cylinder. When the pistons reach the end of the stroke, the flows are switched so that operation is continuous. With the two cylinders in-line the pressure of the feed can add to that of the concentrate, generating an output pressure which is above the concentrate pressure. A Clark pump has been thoroughly tested at CREST at wide ranges of pressure and flow rate and claim that the efficiency was maintained high throughout [31]. The downside is that the largest Clark pump ERD is far too small for the flow rates of the Freshwatermill.

HYDRAULIC MOTOR

Hydraulic motors are used in specific pump-motor assemblies (Figure 2.9 (b)). An axial piston pump (APP), as HPP, and axial piston motor (APM) are coupled together. The pressurised concentrate activates pistons on a swash plate in the motor, transferring its energy to the APP so that the energy usage from the external source is reduced. The pump and motor have fixed displacements, being positive displacement, therefore the recovery is fixed. The pump-motor assembly does not need additional lubrication as this is performed by the water. This could be advantageous to reduce maintenance requirements in case of use in remote areas. Tests at the CREST have shown some corrosion in these devices and favoured the Clark pump, while other developers of renewable-RO systems favoured the hydraulic motor over the Clark pump [31]. These devices are available in sizes suitable for the Freshwatermill.

2.6. HYDRAULIC TRANSMISSION

For the application of a stand-alone wind powered RO systems, operational flexibility is highly desired to make use of as wide possible a range of wind powers.

Although the design of the transmission will not be dealt with in this thesis Ryan Williams and Paul Smith of Eaton Corporation [15] claim that a promising approach is that of using a radial piston pump in the wind turbine nacelle while, on the ground, a bent-axis or an in-line hydraulic motor. This combinations should provide the best efficiency and flexibility as well as provide the possibility to regulate the rotational power delivery speed under variable wind speeds. For the application of a stand-alone wind powered RO system, this type of operational flexibility is highly desired to make use of as wide possible a range of wind powers efficiently.

3
Practical Test

A practical experiment is carried out with the aim of testing the behaviour of the RO system with a varying power supply and to obtain a production curve for permeate against available power. The test will also serve to evaluate whether switching between multiple pressure vessel units results in increased permeate production and/or significantly improves water quality.

The preliminary sizing calculations of the Freshwatermill RO system are computed before the components can be selected and the set-up for the practical test can be designed. In this section the process of this design will be described and the results of the test will be presented and analysed.

3.1. Preliminary Sizing of RO System

Based on the premise that Solteq Energy aims for a maximum production of about 400 m^3 of permeate per day with the Freshwatermill, and assuming it can obtain with a specific energy consumption of about 2.5 kWh/m^3 for seawater desalination with energy recovery, it can be estimated that a power supply of 40 kW is required. To produce 400 m^3 the system would have to operate constantly at 40 kW for 24 hours. The capacity factor (the ratio of actual production over a period of time to the maximum possible production over the same peiriod) of a wind powered RO plant depends partly on the size of its wind turbine, although it is expected to be lower than a fossil fuelled RO plant. The Lagerwey 18/80 has an electrical rating of 80 kW although with a hydraulic transmission conversion the rated mechanical power is expected to increase. Based on its aerodynamics and rated torque it is estimated that rotor shaft can deliver up to 100 kW of mechanical power, although some of this will be lost in the hydraulic transmission. Tests are currently being performed in another study to obtain the power curve of the hydraulic transmission, therefore the estimated rotor shaft power curve will be used as the reference power curve for this test. Calculations for this estimate are described in Appendix A. With a higher rated power the RO system's capacity factor should increase, allowing more permeate production.

3.2. Design of Set-Up

The selection of main components is based on several factors: the required power rating described above; the need of a positive displacement pump for operational flexibility; and the material, which has to be corrosion resistant in order to work with seawater. The largest HPP available on the market that suits the conditions is an axial piston pump with a capacity of 0.225 litres and capable of revolving at a maximum speed of 1800 rpm. This means it is capable of a maximum delivery of 23.4 m^3/h, considering a leakage of about 15 l/min due to clearances for baring cooling, or 561.6 m^3/d of feed water. The same pump manufacturer also provides an axial piston hydraulic motor which can be coupled with the HPP to provide energy recovery. From the review of ERDs in Section 2.9, the hydraulic motor is potentially the most suitable device for the size and operational requirements of the Freshwatermill. The recovery ratio is fixed in advance according to the installed swash plates that change the volume of the motor. There is no need to regulate the recovery ratio by additional

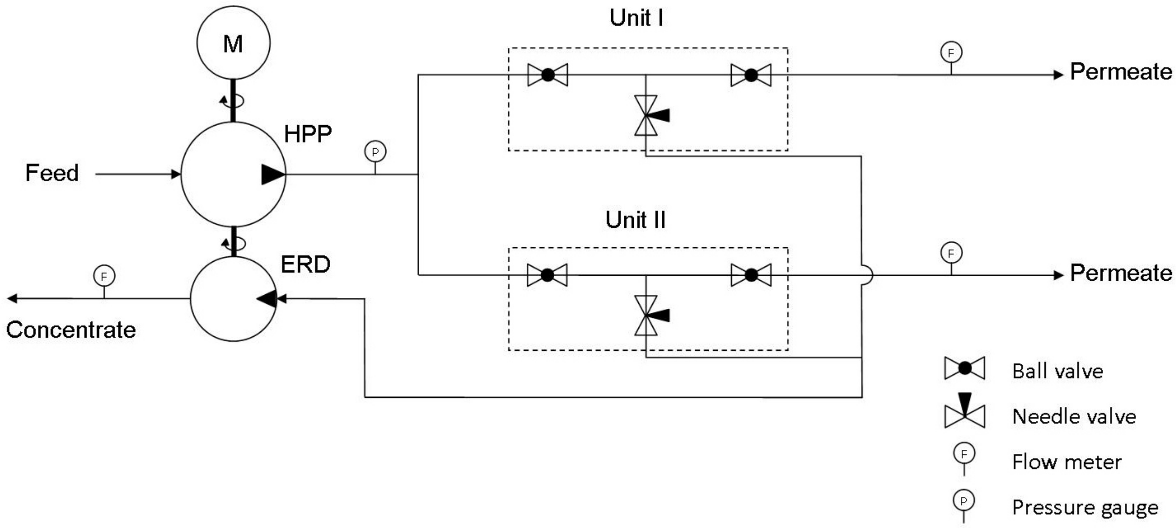


Figure 3.1: Schematic diagram of experimental set-up with two simulated pressure vessel units.

means as it is controlled by the hydraulic motor. This HPP-ERD unit, the specifications of which can be found in Appendix B, will therefore be used for the test set-up. The test will be carried out with a recovery factor of 40%, which is on the low end of the range for mid- to large-scale RO systems and on the high end for small-scale systems of up to 50 m^3/d of product water [9]. The motor will therefore be equipped with a swash plate that gives it a capacity of 0.135 litres, which is 60% of the pump volume. At 40% recovery the maximum permeate production with the selected HPP will be 9.4 m^3/h or 224.6 m^3/d; about half of the desired production for the Freshwatermill. Because of the lack of availability of a larger HPP two of the selected pumps might be required to meet the desired maximum production. This will be verified by the computer model in which the RO system will be scaled appropriately to the Lagerwey 18/80 windmill. Some specifications of the HPP-ERD unit are summarised in Table 3.1.

Table 3.1: Specifications of HPP-ERD unit.

Parameter		Value
HPP displacement	[l]	0.225
ERD displacement	[l]	0.135
Maximum speed*	[rpm]	1800
Maximum pump discharge**	[l/min]	390
Maximum motor flow	[l/min]	243
Maximum operating pressure	[bar]	85
Maximum operating power	[kW]	29
Starting torque	[Nm]	60

* 3.5 bar inlet pressure required at maximum speed
**15 l/min leakage through clearances for baring cooling

The HPP-ERD unit will be connected by shaft to an electric motor which will emulate the power delivered by the windmill via hydraulic transmission. For testing purposes a motor rated 18.5 kW was used, with a variable frequency drive which will be used to control its speed. This will be sufficient to cover a wide enough range to test the performance of the selected HPP-ERD unit and the switching of units. For simplicity, fresh water will be used for the test. Therefore, no actual membranes will be used and thus no desalination will occur. The pressure drop across the membranes will be simulated by needle valves while ball valves will be used to isolate pressure element units when switching between them. The hydraulic pressure drop that would usually occur from the feed to concentrate side of a membrane is not simulated, although this is typically very low with respect to the feed pressure. The needle valves will have to be adjusted at different flow rates to account for the osmotic pressure difference that would normally act on the flux in a normal desalination system. This experiment, therefore purely tests the hydraulics of RO rather than its desalination qualities.

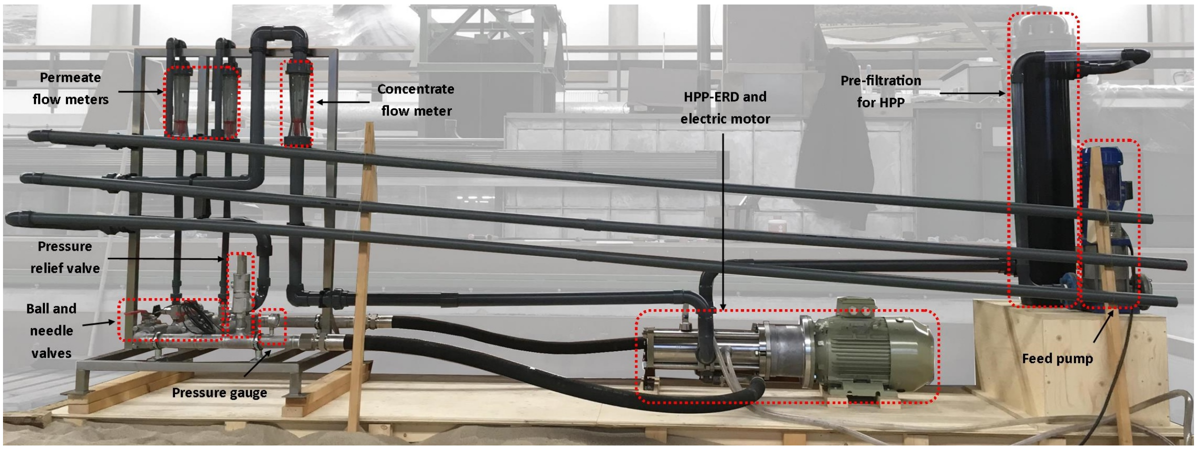


Figure 3.2: Picture of experimental set-up.

Figure 3.1 shows a schematic diagram of the experimental set-up design. As shown in Figure 1.3 in Chapter 1, there is substantial difference in operating power ranges, estimated using ROSA, between a single unit (blue) and two units (red). Based on this estimate, two equal pressure vessel units will therefore be sufficient to test the switching strategy. Each unit will represent five DOW FILMTEC SW30XHR–440i 8"×40" membrane elements in series. Table 3.2 shows the specifications and limits of the membranes in a 5 element unit. The specification sheets can be found in Appendix B. Flow meters are installed to measure both permeate flow rates individually as well as the concentrate flow rate. The sum of these will give the feed flow rate. A pressure gauge is fitted just downstream of the HPP to measure the feed pressure. A picture of the assembled set-up is shown in Figure 3.2 with the main components indicated. Filters were fitted to protect the pump from small particles as well as a feed to overcome the pressure drop of the filters and create some feed pressure required by the HPP. The pressure relief valve is added for safety, to protect the system in case there is an increase in pressure that could damage the system.

Table 3.2: Spcifications and limits of DOW FILMTEC SW30XHR–440i 8"×40" membrane elements

Parameter		**Value**
Maximum operating pressure	[bar]	83
Maximum pressure drop per element	[bar]	0.9
Maximum operating temperature	[°C]	45
Operational pH range	[pH]	2 - 11
Active area	[m^2]	41
Minimum permeate flow for 5 elements in series*	[m^3/h]	2.27
Maximum permeate flow for 5 elements in series*	[m^3/h]	5.05
(For 2 units, permeate flow limits are doubled)		

* for 40% recovery

3.3. STATIC TEST

The first part of the experiment will test the system's performance at static conditions; first with only one unit, then repeated with both units open. It will comprise measuring the permeate flow for a full range of power supply that will vary the pump's speed. At various pump speeds, needle valves will be adjusted to match the feed pressure indicated by the ROSA software simulation at the same operating conditions. Table 3.3 shows the conditions for which the ROSA simulations were performed over a range of feed flows.

3.3.1. RESULTS

Results for the static test are presented below. In Figure 3.3 the measured permeate flow has been plotted against the power supplied to the HPP for both operations with one and two units.

Table 3.3: ROSA parameters

Parameter		Value
Elements per vessel	[-]	5
Recovery ratio	[-]	0.4
Feedwater TDS	[mg/l]	33813
Feedwater temperature	[°C]	25
Feedwater pH	[pH]	7.6
Flow factor	[-]	1

For both cases of single unit (solid line) and double unit (dotted line) the permeate flow increases as a result of increasing power, although by a lesser extent at higher powers. This is likely due to the consequential increase in average osmotic pressure, which is caused by an increase in salt rejection. The minimum feed flow limit for 5 element vessels indicated in Table 3.2 are constrained by permeate water quality. As will be shown below in Figure 3.5, the salt concentration of the permeate would be within 500 mg/l at the flow rate corresponding to a pump power of 2 kW. This was verified while testing the pump's performance over the widest possible range of powers. Therefore, the test was conducted below the minimum flow rate suggested by ROSA. For a single unit, the permeate flow, therefore, spanned between 0.6 to 5.1 m^3/h at powers of 2 to 12 kW. Operating with two units produced slightly more permeate over the same range as the single unit and reached up to 7.8 m^3/h where power from the electric motor reaches its maximum at 18.3 kW. Measurements were not possible below 2 kW due to the limits of the flow meters, although by extrapolation, the starting power for both one and two units is estimated between 1 and 2 kW. The feed pressure at these points, at which the flux is null, should equal the osmotic pressure difference of the system.

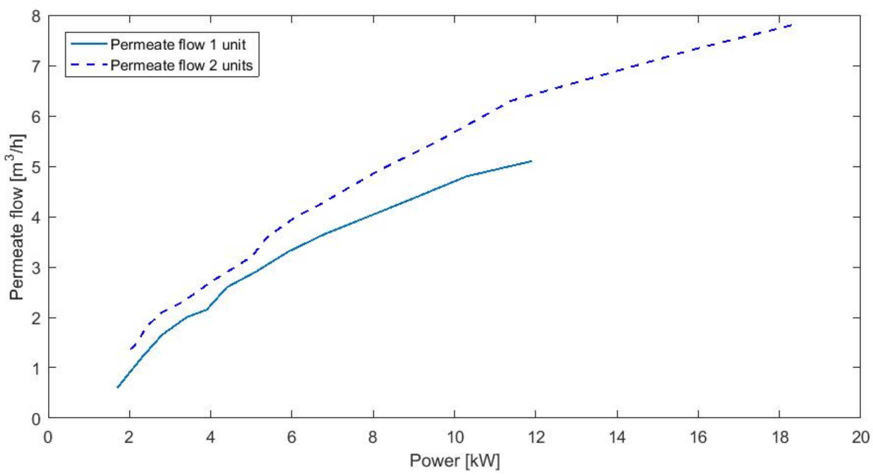


Figure 3.3: Permeate flow against pump power for 1 and 2 units.

Figure 3.4 shows that increasing the permeate flow, which is to a fixed ratio with the feed flow, will influence the feed pressure by a lesser extent with two units rather than one. This is because the membrane surface area is doubled. The flux rate will decrease with a larger surface area as the feed pressure is lower although by a smaller amount than the permeate flow increase due to the increased membrane area. This explains why less power is required to obtain the same amount of permeate with two units rather than one, as shown in Figure 3.3.

Figure 3.5 shows the feed pressure and the amount of TDS in the permeate for the full range of power. At low powers the concentration of salt in the permeate increases exponentially due to the falling feed pressure which reduces the passage of the water molecules far more than the salt molecules, resulting in a higher salt

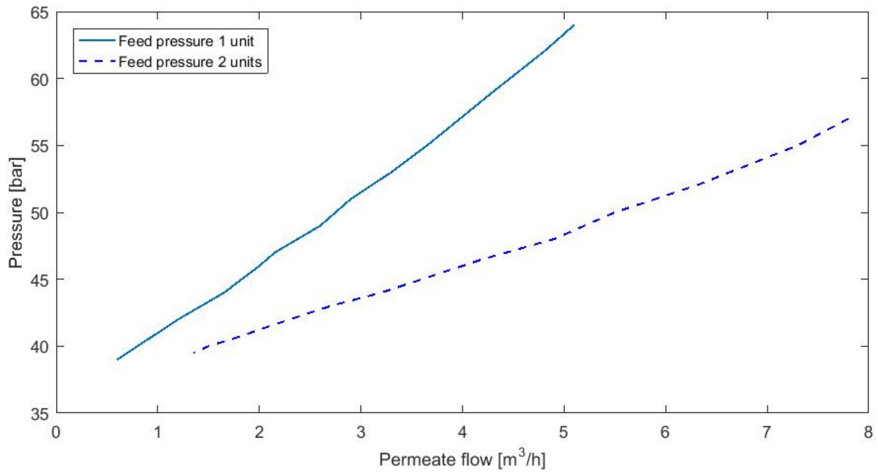


Figure 3.4: Feed pressure against permeate flow for 1 and 2 units.

to water ratio. For the same reason, the permeate salinity with two units is higher than with one unit; the flux is lower and thus more passage of salt molecules with respect to water. For the full operating range the TDS level is, nevertheless, under 500 mg/l, even for operation with two units. At higher power the salinity drops rapidly and levels off. Over a long period of time, with a power supply that varies over a wide range, the permeate quality should therefore average out to be far below 500 mg/l. Operating at low power for extended periods should be avoided to prevent lowering the average permeate quality.

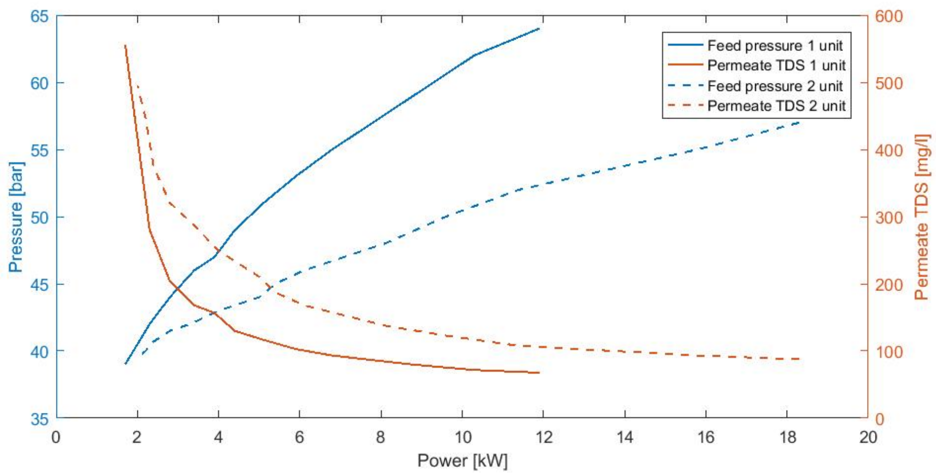


Figure 3.5: Feed pressure and permeate TDS against pump power for 1 and 2 units.

3.4. DYNAMIC TEST

The dynamic test was conducted by simulating a wind pattern with the electric motor at different average wind speeds and measuring the cumulative permeate production and quality for three cases of operation: a single fixed unit, two fixed units, and switching between one and two units. The response of the system to switching units can be verified in addition to determining the most advantageous of the three cases.

A wind pattern that varied between the power range required by a single unit as well as multiple units was generated so that the unit switching strategy could be tested as in normal operating conditions. This pattern was scaled so that the test could be repeated with different average wind speeds, from 4 to 8 m/s, allowing to estimate the permeate production for a given average wind speed distribution. The wind pattern comprised of twelve points separated by a time step of 5 minutes. This gave enough time to switch a unit on or off, if necessary, and adjust the needle valve after every change in power.

The power curve used to convert wind speed to corresponding power values was without gearbox and generator (see Appendix A for details), which reaches just above 100 kW, as shown in Figure 3.6.

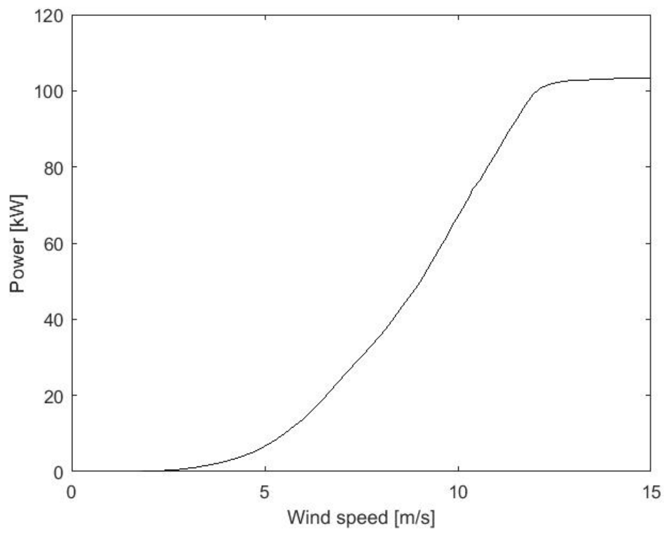


Figure 3.6: Power curve of Lagerwey 18/80 estimated at rotor shaft, excluding gearbox and generator.

3.4.1. RESULTS

Figures 3.7 to 3.11 show the permeate production with different types of operation for a range of average wind speeds. The green and red lines show the permeate production when running constantly on one and two units respectively, while the blue line shows the permeate production when unit switching is adopted. The latter is a combination of single and double fixed configurations. When the available power is below 11.5 kW only one unit is operational while above this power the second unit is switched on. For single unit operation the water production is limited to 5 m^3/h. Any power above 11.5 kW would increase the flow rate and damage the membranes, therefore it would have to be directed elsewhere. Within the 11.5 kW range the permeate flow rate is always slightly higher with two active units because of the larger membrane area.

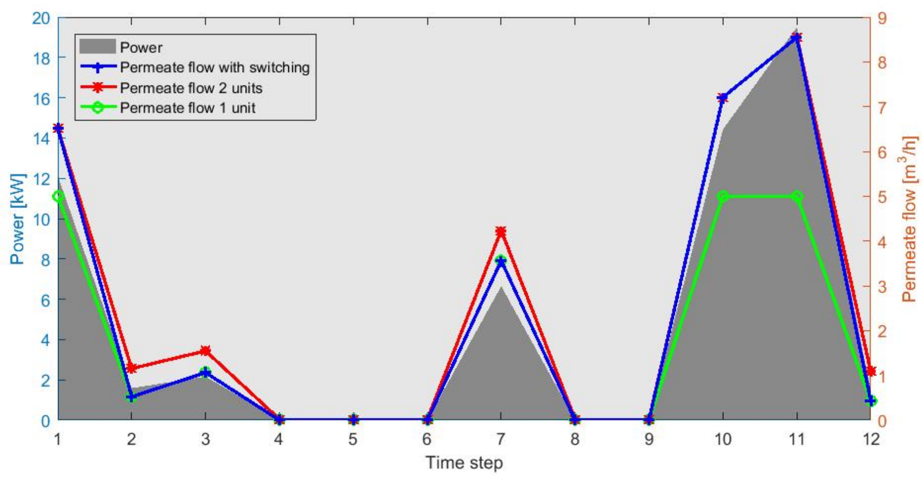


Figure 3.7: Permeate production for average wind speed of 4 m/s.

Overall, operating with two units or with unit switching allows matching the permeate production more closely to the available power. Two units cover the spans of a single unit's operating range, although they can operate at higher powers at which a single unit would not. At low powers, however, the permeate quality is expected to be lower with two units than with one. This is where unit switching can be advantageous. It combines the wider operating range of two units, which is particularly useful at high power winds, while maintaining a higher permeate quality at low power winds, at which it drops drastically, sacrificing a small amount of permeate.

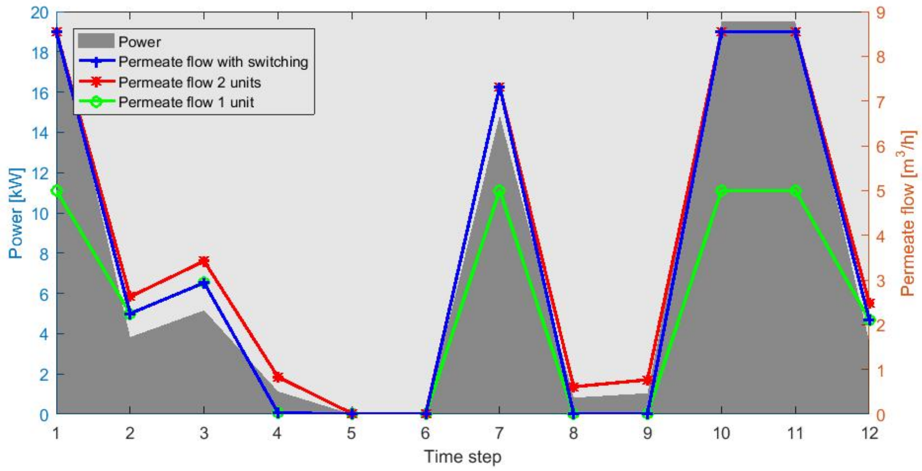


Figure 3.8: Permeate production for average wind speed of 5 m/s.

At higher average wind speeds the extent of the operating range becomes increasingly more important as the power rarely drops to levels corresponding to poor permeate quality, and large parts of the power are available above the range of a single unit. In Figure 3.11, showing the production for an average of 8 m/s, it is clear that in the first and last two time steps the power is limited by the electric motor. The power at which the permeate flow for two units reaches its maximum limit is at 30 kW as found by extrapolating the permeate production curve in Figure 3.3. However, the HPP-ERD unit is the limiting factor as it would reach its maximum speed at a feed pressure of 62 bar, at which the power usage will be 26.1 kW. Nevertheless, the possible operating range of an actual RO system with two units will be higher than that shown in the test results.

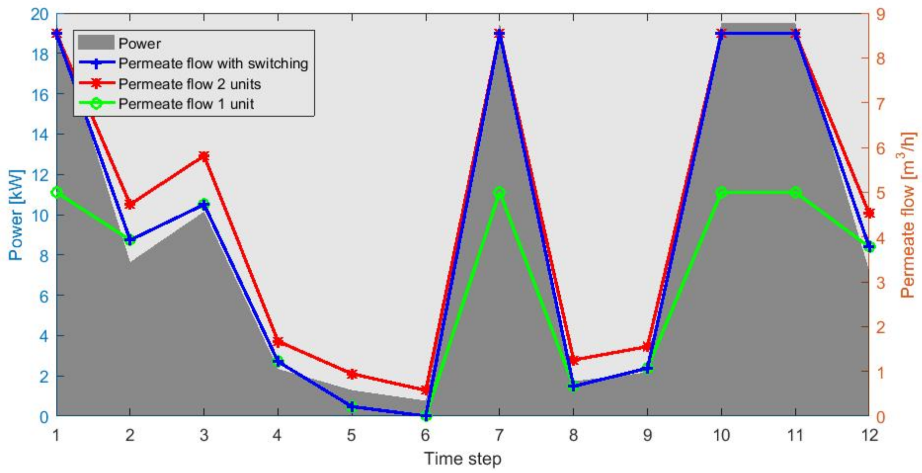


Figure 3.9: Permeate production for average wind speed of 6 m/s.

On the contrary, at low average wind speeds it may be more advantageous to operate with a single pressure vessel to improve the average permeate quality. Particularly in the very low powers, below 3 kW at which the difference in permeate salinity between two and one units is more than 100 mg/l and rapidly increases above 300 mg/l at even lower powers.

The average permeate production and TDS for each of the three cases tested and for each average wind speed

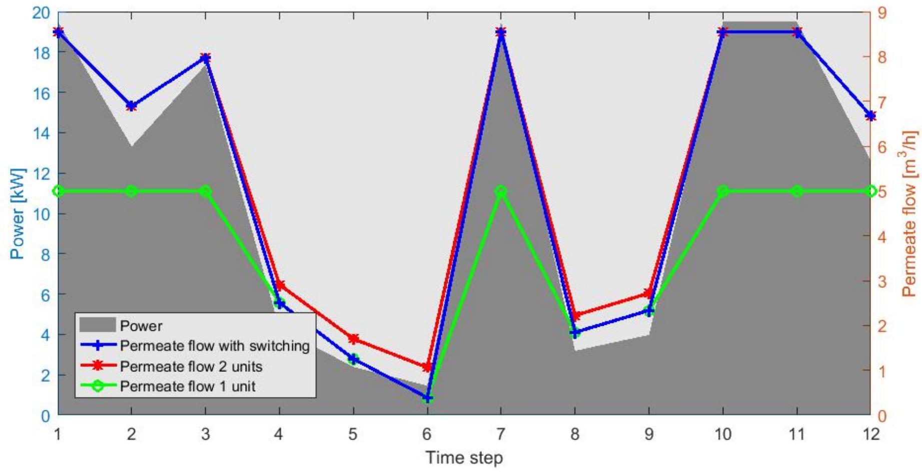


Figure 3.10: FPermeate production for average wind speed of 7 m/s.

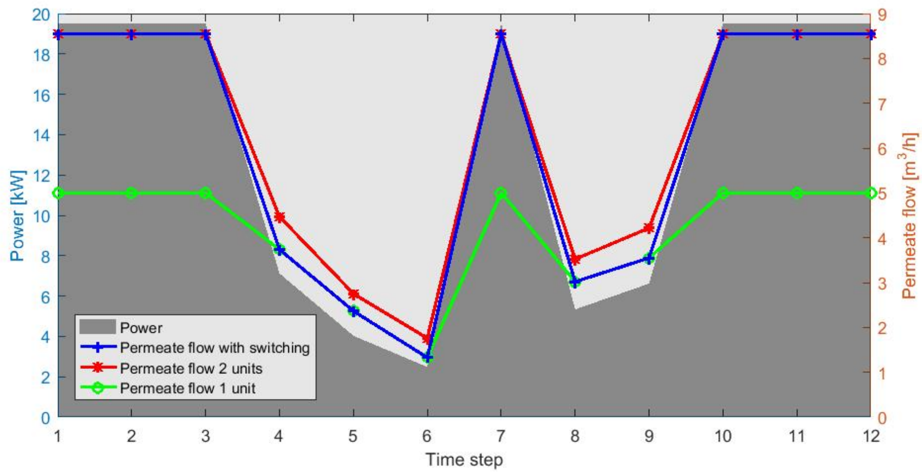


Figure 3.11: Permeate production for average wind speed of 8 m/s.

are shown in Figure 3.12. From these bar graphs it is clear that the permeate production is always the highest when operating with two fixed units although only marginally higher than with unit switching. Assuming the full power range of the HPP-ERD unit could be reached, the permeate production for switching and two fixed units could be expected to be higher for the higher average wind speeds than displayed in the graph, as these were limited by the electric motor. These showed a larger response to change in wind speed than the single unit; about 20 m^3/d per 1 m/s increase against just above 10 m^3/d for the single unit.

The effect of wind speed on the variation of permeate salinity is surprisingly small and contained within an acceptable quality range. For two fixed units the salinity was higher than for the other two cases, as expected. Despite this, at the lowest tested average speed of 4 m/s, at which the TDS level is highest, it is still below 160 mg/l, which is considered a very good quality permeate. For the case of unit switching, the TDS stays marginally above those of single unit operation. This clearly shows that the switching units combines the better aspects of the two fixed cases; high production at high wind speeds and low salinity at low wind speeds. While the TDS for two units decreases slightly with increasing average wind speed, for one unit and switching units there is no visible trend. This is likely due to the nature of the chosen wind pattern. At low average wind speeds there are time steps in which there is no production (4-6, 8-9), however at higher average wind speeds the same time steps will produce a small amount of permeate of low quality, adding to the average TDS level of the full time series. A different wind pattern may show decreasing permeate concentration, as would be expected, with increasing average wind speed.

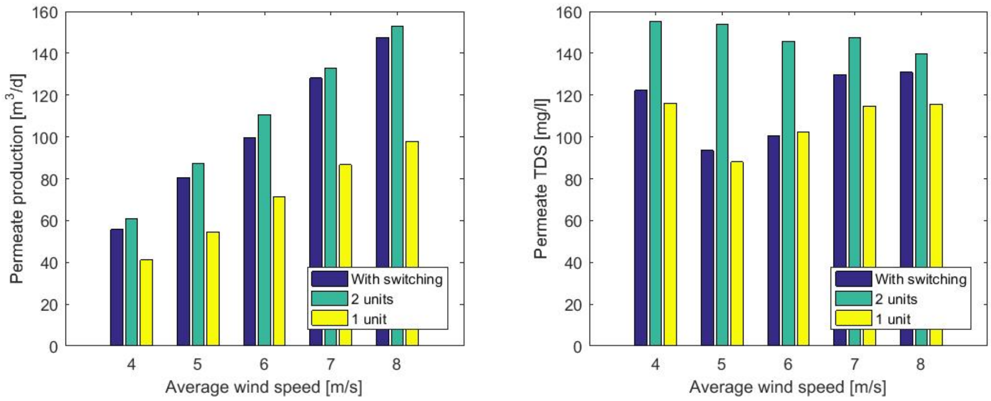


Figure 3.12: Average permeate production (left) and TDS (right) for three test cases at different wind speeds.

3.5. OBSERVATIONS

The following observations and considerations were made about the experimental set-up and procedure used to test the system.

- It was noted that when starting the pump after a long period of inactivity (several days) the variable speed drive did not have sufficient torque to start the pump, despite it having a high starting torque setting. The HPP and ERD were drained from their drainage ports when the system stopped running and the system had to be primed with fresh water in order to give it sufficient lubrication for start-up. When this was not sufficient the motor fan was jerked from side to side to ensure the water came into contact with all moving parts of the HPP and ERD. The finalised system should have drainage pipes with outlets slightly higher than the drainage ports on the pump to ensure that the system does not empty and dry out.

- The dynamic test was only carried out for a single wind pattern. Repeating it for different patterns of various average wind speeds, or by extending the time of each simulation to have a more complete spectrum of operation would give more accuracy to the results.

- The pressure drop across the feed-concentrate side of a membrane is not simulated in the test set-up. With actual membranes the ERD would therefore operate at a slightly lower pressure than and in this test with valves and fresh water. The effect of this difference is considered to be very small, however, and would not compromise the aim of the test. Additionally, pressure losses in the pipes are not measured, although these are expected to be similar in the final operational RO plant.

- Carrying out the test with different time steps would have been useful to give a more complete range of operating conditions. The response of the hydraulic system will have to be measured to understand how fast the pump speed will vary in response to the changes in wind speed. A smaller time step would give higher resolution, although this is partly limited by the flow meter accuracy.

- Warning or caution messages will appear whilst running simulations in ROSA if the feed flow is too low. In the hydraulic test the pressure will be allowed to reach pressures lower than these warnings, to a minimum of 35 bar. At this feed pressure the permeate quality would be low however considering that the pressure is expected to fluctuate with wind speed it will not always be so low and therefore the average permeate quality for a long duration will be higher.

- The noise produced by the HPP-ERD and electric motor at the maximum power was very high. Substituting the electric motor with the hydraulic transmission motor might reduce this noise slightly, however may be necessary to keep the unit within a sound isolated container in order to minimise undesired sound pollution.

3.6. CONCLUSION

From the static test, the performance of the HPP-ERD system combined with the simulated membranes was quantified by measuring static points of pressure and flow rate at various powers. From these, as well as the dynamic test at various average wind speeds it was possible to estimate the production of permeate using the chosen equipment. With this, the first secondary objective is answered.

To answer whether the strategy of switching units is beneficial to the amount and quality of permeate produced by the Freshwatermill we must consider the permeate quality in particular. Initially, it was found that the minimum flow rate limits suggested by ROSA could be exceeded by a large amount before the TDS level increased above 500 mg/l. Moreover the production with two units is slightly higher, while covering the same range and more, than with one unit. In the dynamic test it was confirmed that the average permeate salinity remained far below 500 mg/l even for low average wind speeds, and the effect of wind speed on salinity was considerably small. In the case of the Freshwatermill, which may be applied in areas where it will be the only source of fresh water, once a satisfactory permeate quality is achieved, the quantity of permeate produced becomes the most important objective. Switching units is beneficial in terms of permeate quality, although considering that it would require automated actuators with a control system to operate the ball valves, the system would become much more complex and expensive for a rather small improvement in water quality. It can therefore be affirmed that, for the chosen components and operating parameters, the configuration of two units is the most advantageous in terms of water production and makes the system cheaper, more robust and reliable due to its simplicity. The continuation of this report will therefore only consider the configuration with two units.

For a case in which it is necessary to maintain a particularly high permeate quality, the lowest part of the flow rate range with the lowest permeate quality could be dumped. This would allow maintaining a higher average quality, while only sacrificing the lowest, least significant part of the permeate flow range.

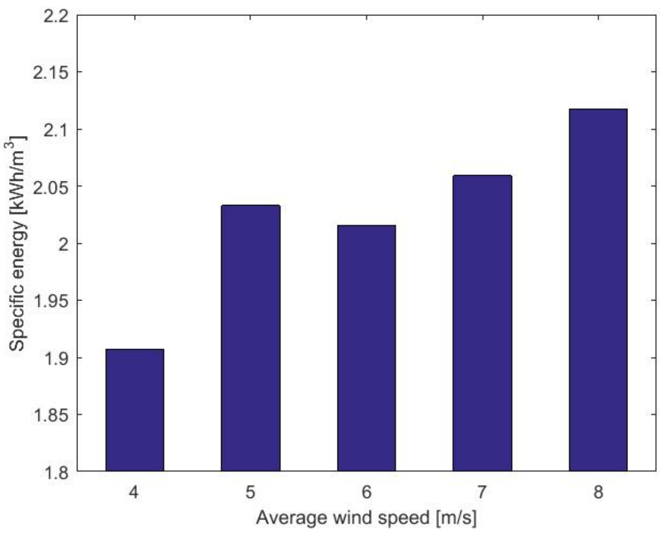


Figure 3.13: Average specific energy consumptions for two units.

Figure 3.13 shows the average specific energy consumption for two units at different average wind speeds. The range, between 1.9 and 2.13 kWh/m^3 from 4 to 8 m/s average wind speeds, is within the range specified by the HPP-ERD manufacturer. Systems with energy recovery usually fall around 2.5 kWh/m^3 [32]. The specific energy consumption increases with wind speed due to the fact that hydraulic losses are proportional to the square of the fluid velocity, which increases with power. Considering the low specific energy consumption measured in the test the HPP-ERD unit confirms its high level of performance and versatility in operating efficiently over a wide range of speeds and pressures. In addition, the configuration of 8"×40" membranes in two pressure vessels proved to be suitable in covering the flow range provided by the HPP. The same configuration can therefore be confirmed for the simulation modelling in Chapter 4. A future step to take, once the power curve from the windmill and transmission will be successfully measured in a separate test, is to relate the water production and feed pressure of the RO system directly to the wind speed by combining the hydraulic transmission power curve to the results obtained in this test.

4

Computer Simulation

From the practical test presented in Chapter 3 it was concluded that the RO system that will be coupled to the windmill transmission of the Freshwatermill will comprise a axial piston pump and motor HPP-ERD with two pressure vessels in parallel configuration operating continually. Such RO system is limited by the pump and energy recovery power centre which, considering the operating pressure, reaches its maximum rotational speed at a power of 26 kW. The windmill of about 100 kW power rating is almost four times that of the RO system, leaving plenty of power for more water production. A computer model is therefore created to understand how many of the same RO systems that comprise one HPP and two units can be coupled to the windmill transmission to maximise the water production. A dynamic simulation will be performed to estimate the amount of permeate that can be expected from using multiple RO systems. Using these simulations the economic benefit of coupling additional RO systems will also be quantified.

This chapter will present the design of the computer model, the verification of the model and the simulation results that will enable quantifying the water production for different installed RO capacities and at different wind conditions as well as their relative financial viability.

4.1. Description of Computer Model

The computer model, based on Simulink software, is designed to represent the behaviour of the full scale Freshwatermill in a dynamic simulation. Using Simulink it is possible to simulate the start-up behaviour of the HPP-ERD, given its starting torque, and the inertia of the system which affects its performance in dynamic operation.

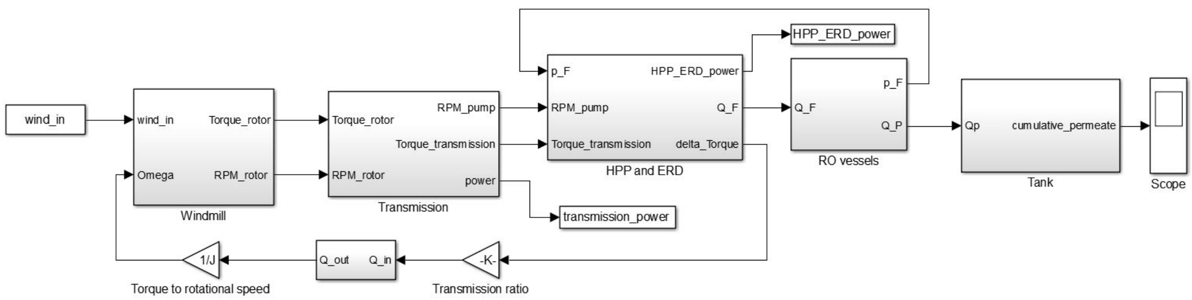


Figure 4.1: Main blocks of Simulink model.

The model consists of five blocks, shown in Figure 4.1; the first four being fundamental to characterise the behaviour of the overall system, whereas the last block is merely for the purpose of quantifying the production of fresh water.

4.1.1. WINDMILL

The first block is the windmill. It receives a series of wind speed data as input with a given time interval per value. Two look-up tables are used to give the wind speed's corresponding torque and rotational speed values from relative torque and rotational speed curves of the windmill. The rotational speed curve is approximated from the power curve of the Lagerwey 18/80 turbine by using the tip-speed ratio, which for this turbine is constant below rated power, and the torque curve is derived by dividing the power by rotational speed (see Appendix A).

The second input to the windmill block is the change in speed given by the acceleration, or deceleration, in rotational speed resulting from the difference between the torque delivered by the hydraulic transmission and that of the HPP-ERD during the previous time step. With varying wind speed the instantaneous power of the HPP-ERD will therefore not be precisely correlated to the power delivered by the windmill due to the overall inertia of the system. The acceleration is given by the difference in torque, dQ divided by the system's inertia, J. The overall inertia is given by the sum of inertias of the windmill rotor, the hydraulic transmission and the HPP-ERD. The mass of the windmill rotor at 900 kg is however much higher than the HPP-ERD components, and the inertia of the hydraulic transmission is yet to be calculated in a separate study. In the model the overall inertia therefore comprises the rotor's inertia multiplied by a factor of 1.2 to account for the rest of the system. The two-blade rotor can be considered as a rod that rotates around its centre. It's inertia J can be calculated as shown in Equation 4.1

$$J_{rotor} = \frac{1}{12} m l^2 \tag{4.1}$$

where m and l are the mass and length of the rod, respectively.

The integral of the acceleration due to the difference in torque over a single time step will result in a change in rotational speed. This is added to the rotor's speed to give the resulting new rotational speed (see equation 4.3)

$$\omega_{new} = \omega_{t-1} + d\omega_{d\tau} \tag{4.2}$$

$$= \omega_{t-1} + \int_{t-1}^{t} \frac{d\tau}{J} dt \tag{4.3}$$

where τ is torque in Nm, ω is rotational speed in rad/s and t is the time step.

The difference in torque between the new windmill speed and the new rotational speed is also added to the windmill torque so that the torque also converges towards that of the HPP-ERD. The torque of the HPP-ERD will depend on the feed pressure created by the membranes, however, this will be elaborated in a later section.

4.1.2. TRANSMISSION

The Freshwatermill uses a hydraulic transmission to transfer power from nacelle to ground. A positive displacement pump is connected directly to the rotor shaft and, while rotating at the rotor's speed, it pumps the working fluid (water) to one or more positive displacement hydraulic motor(s) on the ground which will be coupled to a HPP. Tests are being performed in parallel with this thesis to measure the performance and efficiency of the hydraulic transmission. The transmission block is therefore modelled by simply multiplying the torque by an assumed efficiency value and changing the rotational speed at which the power is delivered by the hydraulic motors. An efficiency of 95% is chosen as this is in line with the expected by Solteq Energy. Once the transmission test is concluded, the resulting performance curves can simply be integrated to this model. The transmission ratio is the maximum speed allowed by the HPP-ERD (1800 rpm) divided by the maximum speed of the windmill rotor (120 rpm). This is multiplied by the rotational speed and divided by the torque coming from the windmill block.

4.1.3. HPP-ERD

The HPP and ERD are positive displacement devices and therefore their flow rates are considerably unaffected by pressure, especially for the operating pressure range of the RO system (see Appendix B for component specifications). The flow rates are thus directly proportional to the rotational speed. Combining Equation 4.4, which describes the power of the rotating pump shaft (P_{sh}), and Equation 4.5, expressing the hydraulic power imparted on a fluid to increase its velocity and pressure, it can be seen that if the ratio of flow rate to rotational speed is constant then the torque is a function of pressure alone.

$$P_{sh} = \tau\omega \tag{4.4}$$

$$P_{hydr} = Qp \tag{4.5}$$

The HPP-ERD block therefore uses the transmission speed to dictate the flow through either device, according to its volumetric displacement and the RO feed pressure to calculate the torque required by the HPP or added by the ERD. The torque required by the HPP is then subtracted from the one supplied by the ERD and hydraulic transmission. The resulting difference in torque ($\Delta\tau$) is an output used to calculate the change in windmill rotor speed which will allow the system torque to converge towards equilibrium. The feed flow dictated by the speed of the HPP is active only when $\Delta\tau$, and thus available power, is positive.

The torques required by the HPP and that generated by the ERD are derived using Equations 4.4 and 4.5 as well as using the parameters from Table 3.1. The relations used for the HPP and ERD as well as their efficiencies as a function of pressure are derived from the specification sheets presented in Appendix B and applied in form of look-up tables in the model.

The start-up behaviour is modelled by verifying whether the HPP was operational in the previous time step before switching the required torque to the starting torque of the HPP-ERD of 60 Nm.

4.1.4. RO VESSELS

The feed flow from the HPP is fed into the RO vessels block which produces two outputs; a permeate flow of 40% of the feed flow, dictated by the fixed displacement of the ERD, and a feed pressure which is fed back to the HPP-ERD block to determine the system torque.

To obtain the feed pressure an attempt was made to follow the method used by ROSA which determines the permeate flux per element in an iterative process, given a feed pressure and feed flow rate, and calculates the net driving pressure across each element. The idea was to adapt this calculation to obtain the feed pressure given a fixed recovery ratio and feed flow rate. This would allow to easily make changes to the water parameters, such as salinity, temperature and pH, as well as the types of membranes used. This method was ultimately not applied as the results did not correspond with ROSA, most likely due to inaccurately approximated concentration polarisation factors for each element. Further research into this calculation would be required to develop such dynamic model.

Alternatively a series of feed pressures at different feed flow rates was obtained using ROSA with the same elements and at the same conditions specified in Tables 3.2 and 3.3. These were then applied in the model using look-up tables. To change the water parameters or membranes being tested, a new series of feed pressures needs to be obtained and loaded in the Simulink script.

4.2. MODEL VERIFICATION

The model is verified via a comparison with the test results, which are in accordance with ROSA. For an incremental series of wind speeds, from 0 to the windmill's rated wind speed of 12.5 m/s, the feed pressure and permeate flow of the model simulation were plotted against power and compared to the equivalent practical test values. These are shown in Figures 4.2 and 4.3.

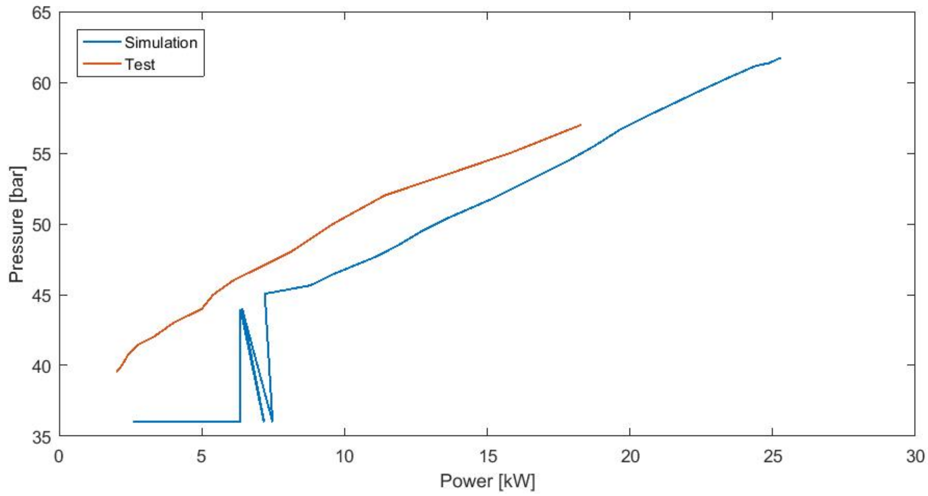


Figure 4.2: Feed pressure vs. power for model simulation and practical test.

The pressure curves show the same gradient, although the model simulation gives higher powers than the test results for the same pressures. The same can be said for the permeate flow values. They show a similar profile, however the simulation has a slightly higher power consumption. The slight difference of about 2 kW is believed to be caused by a mismatch in the efficiency estimations of the HPP and ERD, although the resulting difference is not significantly large. The simulation results show some oscillations in the range between 6 and 7 kW. This behaviour is due to the inertia given by the starting torque of the RO pump.

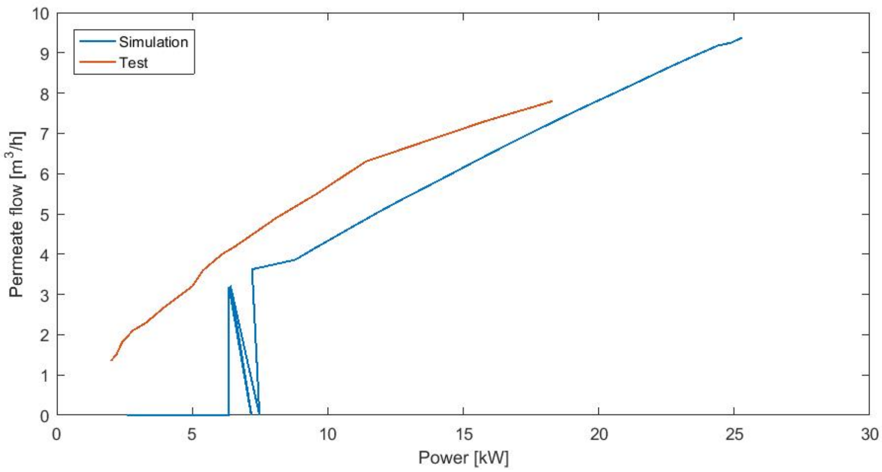


Figure 4.3: Permeate flow vs. power for model simulation and practical test.

The relation between feed pressure and permeate flow of the simulation is also compared to the test. Figure 4.4 shows that there is a perfect match between the two.

A final verification is made to test the dynamic behaviour of the model. This is done by running the same wind data as for the 8 m/s average wind speed dynamic test performed with the practical test set-up. The permeate productions are compared in Figure 4.5. Considering that the computer model simulates a much larger inertia than is present in the test set-up and that the electric motor of the test rig maxed out at a power lower than the windmill's rated power, the two permeate flow profiles are considerably similar. The simulation shows an oscillating behaviour at the lowest powers as the torque at this point drops below the starting torque of the HPP-ERD.

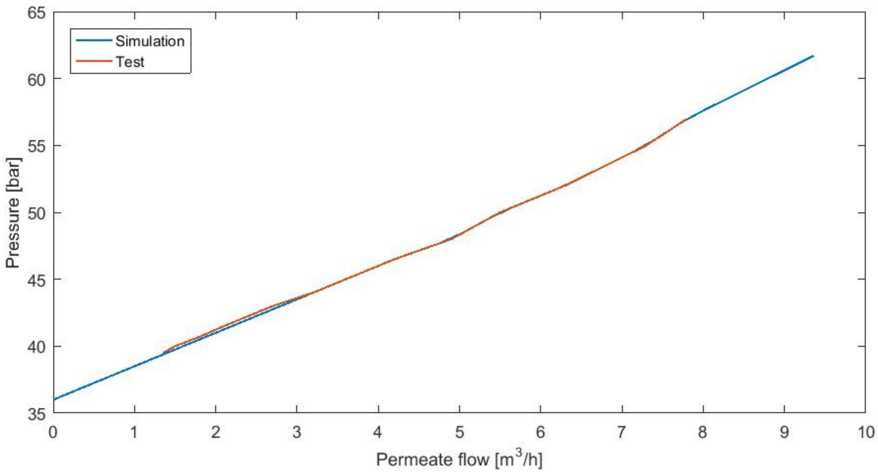


Figure 4.4: Feed pressure vs. permeate flow for model simulation and practical test.

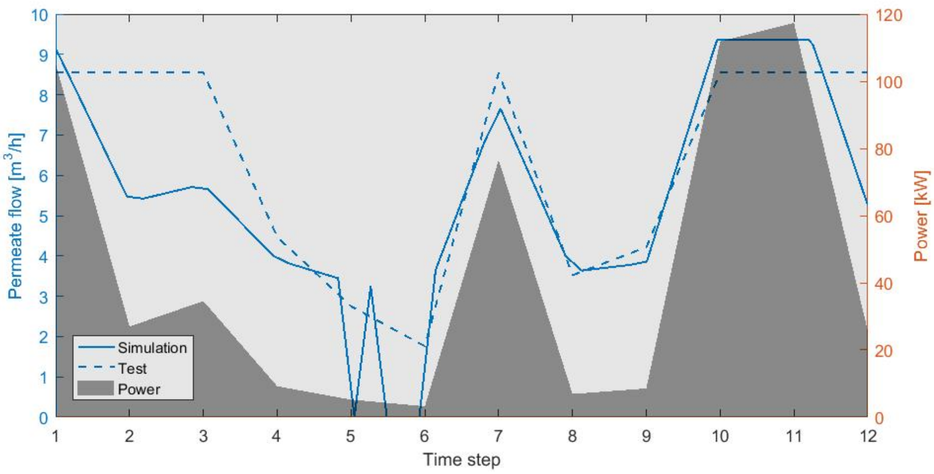


Figure 4.5: Permeate flow for model simulation and practical test under dynamic power conditions.

4.2.1. MULTIPLE RO SYSTEMS

So far, the verifications of the model have been performed with a single RO system; one HPP-ERD powering a set of two pressure vessels. Due to the nature of the computer model which calculates the starting torque the maximum number of RO systems that can be operated by the windmill must be calculated assuming the RO systems are in series. A comparison is also made to explain whether the RO systems should be installed in series or parallel configuration on the hydraulic circuit. Having multiple hydraulic motors in series implies that all the motors will operate with the same flow rate of the hydraulic working fluid passing through either motor. If one hydraulic motor is not operational, it will block the hydraulic fluid from circulating in the rest of the circuit. On the other hand, the generator that will be installed on the hydraulic system to make use of excess energy from the wind can be installed in series with the RO coupling motors as its torque will depend on the power withdrawn from the generator, which can be very low when no power is withdrawn.

A simulation is performed to demonstrate the behaviour of the system when multiple RO systems are coupled to the hydraulic transmission in series. The results are plotted in Figure 4.6 in form of permeate flow to available power.

As the number of RO systems coupled to the transmission increases, so does the load on the windmill and the starting torque. For this reason the starting power of a single RO system is lower than two with systems, which is in turn lower than with three systems. Each HPP acts as a resistance to the flow of the hydraulic transmission. With 3 RO systems the starting power is a high value of about 60 kW compared to the 12 kW

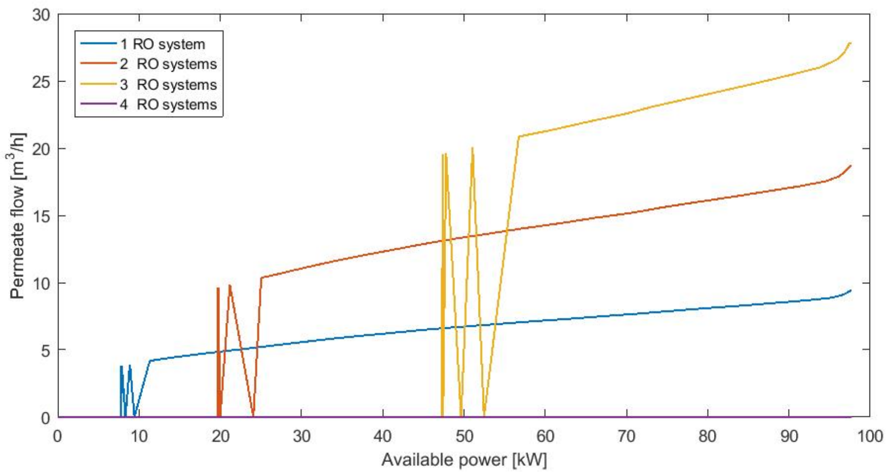


Figure 4.6: Permeate flow vs. available transmission power of 1, 2 and 3 RO systems coupled to the hydraulic transmission in series.

of a single RO system. Having said that, the production of fresh water with more systems starts at higher flow rates and increases more rapidly with power, as can be seen by the different gradient of the lines. In this series configuration a trade-off must therefore be made between low starting torque and high-end power. The fluctuations that appear at the start of each line are due to the inertia of the system which makes the model hesitate to start the pump with each successive iteration until the power is sufficiently high for the pump to remain active.

It can also be noted that when the simulation is run with four RO systems the starting torque is too high for the HPP to start at all. This means that the maximum possible number of RO systems (with the specific equipment being tested) is three.

If the RO coupling motors are installed parallel to one another, valves can be used to isolate each motor so that one can be operated at a time. In this case, each additional motor would be added when the power increases enough to overcome the starting torque of the next motor. The amount of motors in operation will depend on the amount of power available and will follow the intervals shown in Figure 4.6. The maximum number of systems in parallel remains three. This is because the starting torque of each RO system in parallel will be that of a single system (60 Nm), although they will start at the power corresponding to the same amount of systems in series. The difference is that in series the amount of RO systems in operation cannot be changed. The behaviour of the water production in the case a flexible parallel configuration, with valves to control the number of operating RO motors, is shown in Figure 4.7.

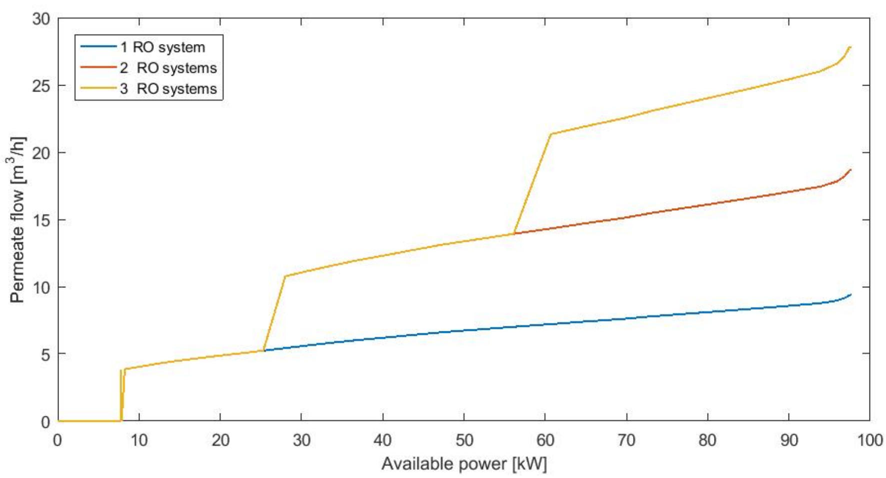


Figure 4.7: Permeate flow and operational RO systems vs. available transmission power in flexible parallel configuration.

From Figure 4.7 it can be seen that with multiple systems the permeate production steps up when the power is sufficient to run additional systems, enabling to widen the operating range. The parallel configuration offers more flexibility with valves as the system is able to switch between different numbers of RO systems, maintaining a low starting torque at low powers with a single RO system while also making use of the higher powers with up to three RO systems.

It can therefore be said that the a parallel configuration for multiple RO systems is more beneficial if automated valves are used to isolate each RO coupling motor on the hydraulic circuit. As simulated for the parallel configuration (Figure 4.7), the automated valves that control the activation of a new RO system would have to me regulated according to the increase in power available from the windmill. If the new RO system valve was immediately fully opened, the flow to divide equally between all the active RO units. This would represent a different behaviour from the one modelled. This is undesired An example of the parallel configuration is shown in Figure 4.8 with two RO systems. Dynamic simulations at different wind speeds will be performed using the parallel configuration and a control system that will change the number of RO systems on the model depending on the available power, and thus starting torque. Once the number of RO systems is determined by the controller, the torque delivered by the transmission is divided by this number, while the difference in torque between the HPP-ERD and transmission, as well as the permeate flow, is multiplied by the number.

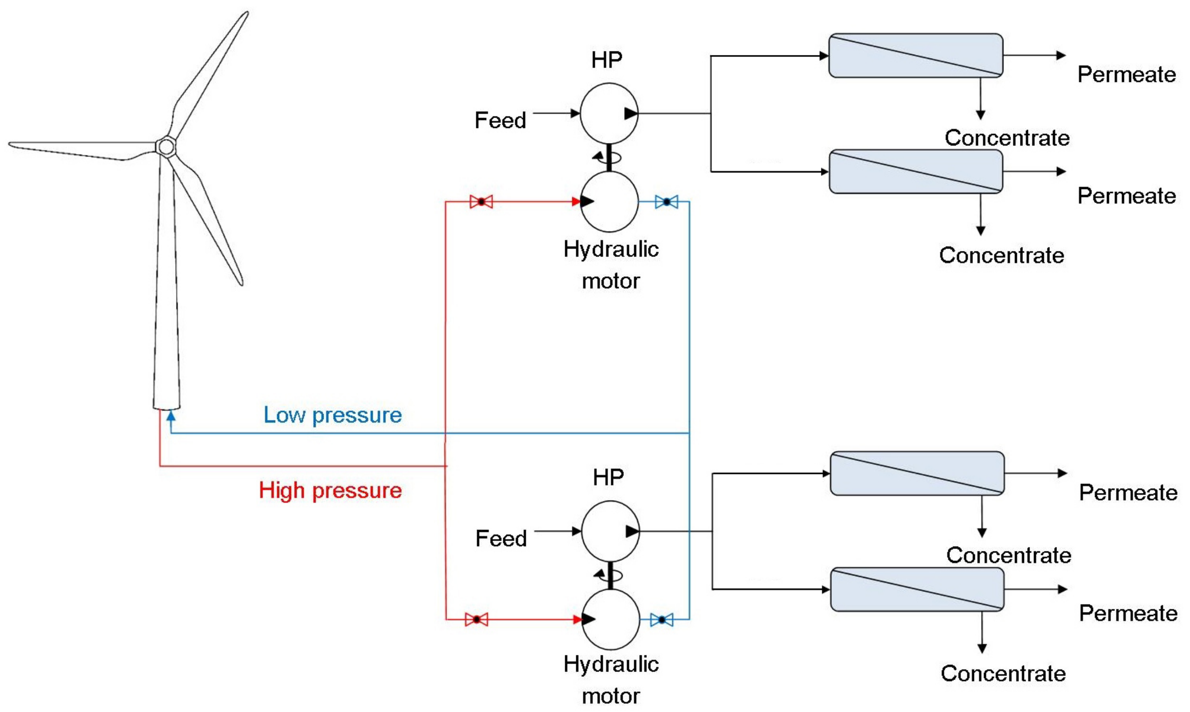


Figure 4.8: Two RO systems in parallel configuration with valves on hydraulic transmission.

In parallel configuration the start-up of each RO pump does not show many hesitations as for the series configuration because the inertia felt by the transmission is only given by a single pump's starting torque at a time rather than multiple ones.

Figure 4.9 shows the limits of power within which each number of RO system configuration can be operated.

4.3. DYNAMIC SIMULATION RESULTS

A dynamic simulation will be run with up to three pumps in parallel configuration to understand what the permeate production potential of the system is with 1, 2 and 3 RO systems and in different wind conditions.

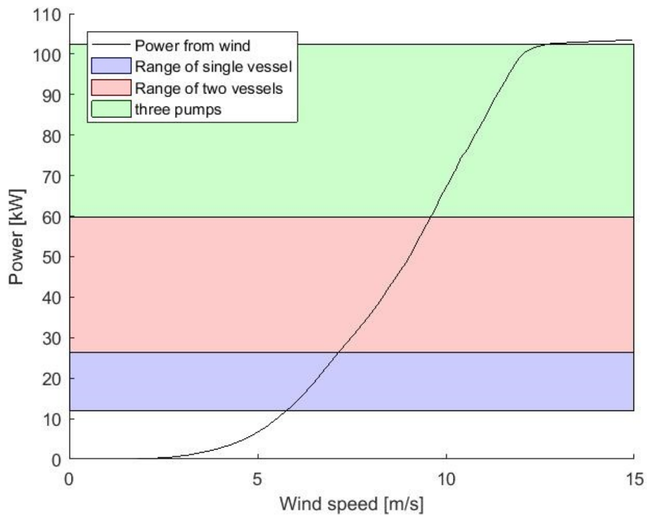


Figure 4.9: Power range within which each RO system can be operated.

The simulation will be run with exactly one year worth of wind data, measured with a 10 minute time interval. This data, shown in Figure 4.10, comes from a location with an average wind speed of 9 m/s and the Weibull parameters shown in Table 4.1. This data is then scaled to averages of 4, 6 and 8 m/s so that the simulations can be run with different average wind speeds but with a similar wind pattern. The Weibull shape and scale parameters of the original and modified wind data are presented in Table 4.1. Scaling of the wind data is simply done by multiplying each value by a given factor to obtain a new overall average wind speed. It is recognised that the Weibull parameters, and thus the wind energy, will not be scaled accordingly although this method is considered reasonable for the purpose of this study.

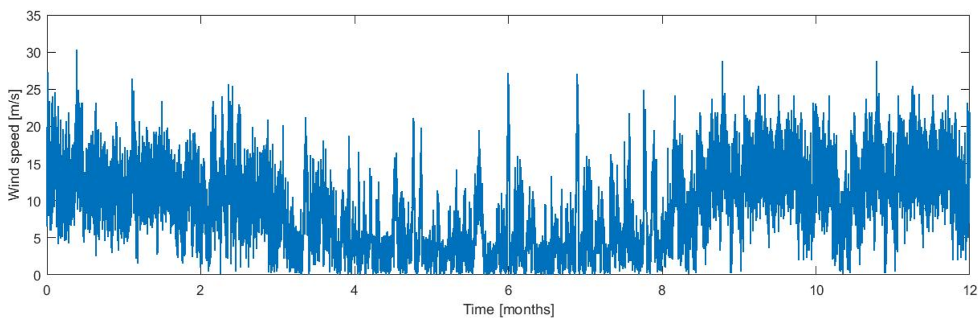


Figure 4.10: Yearly wind data with average wind speed of 9 m/s.

The yearly wind speed data shows clear seasonal variations. The first and last three months of the year show higher wind speeds than the six months in between. These variations within the year will help to understand the relative performance of using different numbers of RO systems. It is expected that the at lower wind speeds the single RO system will have a higher production as it has a low starting torque allowing it to operate in low wind speeds.

Figures 4.11, 4.12 4.13 show the cumulative permeate production for 1, 2 and 3 RO systems with average wind speeds of 4, 6 and 8 m/s respectively.

At a 4 m/s average the permeate production of all configurations are similar because the wind power is mostly in the region of a single RO system. Therefore, at this speed the investment of additional equipment to increase the production potential may not be justifiable. There are also long idle periods in the middle months of low wind speed when the power is not sufficient to overcome the starting torque of a single system. The last 3-4 months, when the wind power is higher, show the advantage of having additional RO systems as the

Table 4.1: Average wind speed and Weibull parameters for 10 minute interval wind data.

Parameter		**Value**			
Average wind speed	[m/s]	9*	4	6	8
Weibull scale parameter	[-]	9.67	4.28	6.42	8.56
Weibull shape parameter	[-]	6.79	6.79	6.79	6.79

* original data

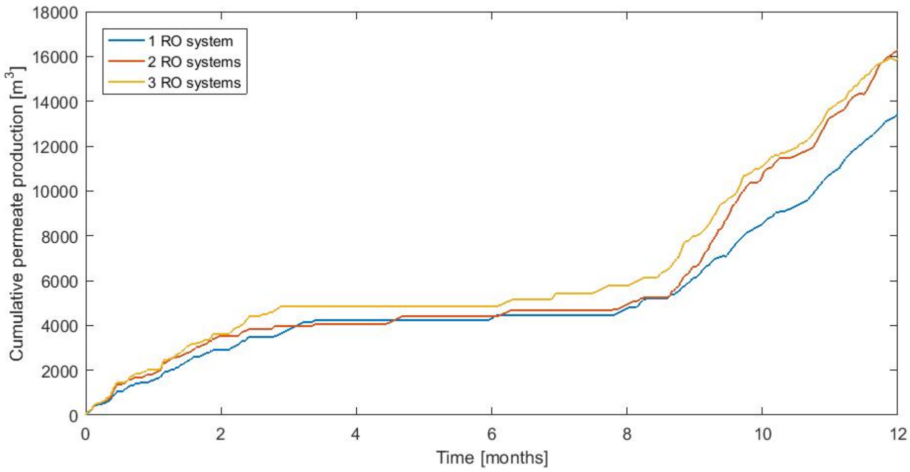


Figure 4.11: Cumulative permeate production of 1, 2 and 3 RO systems coupled to the hydraulic transmission at 4 m/s average wind speed.

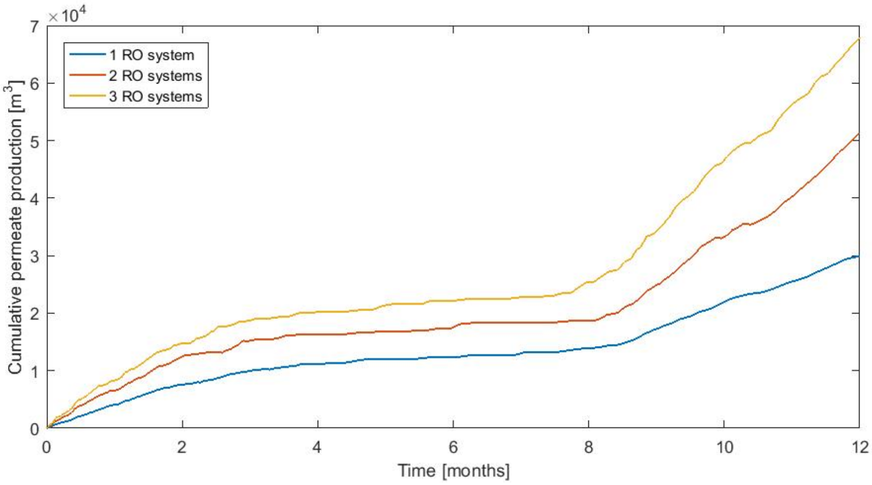


Figure 4.12: Cumulative permeate production of 1, 2 and 3 RO systems coupled to the hydraulic transmission at 6 m/s average wind speed.

2 and 3 RO system configurations separate from the single RO configuration which produces less permeate. From looking at Figure 4.7 it is expected that the higher number of RO system configurations should never produce less than the configurations with fewer numbers as they include the options of switching to fewer RO systems. At this low average wind speed this is not the case however, as the inertia of adding an RO system to the transmission has an effect on the power response, explaining why the production of larger systems can drop below those of smaller systems.

For the 6 m/s average wind speed data there is a much larger difference in production between the 1, 2 and 3 RO system layouts as the larger systems can make use of the higher powers to produce more permeate.

The idle periods are much shorter due to the higher average torque provided by the windmill. The permeate production with 3 systems reaches about 68000 m^3 at the end of the year, which averages 186 m^3 per day, as opposed to 44 m^3 per day for the equivalent system at 4 m/s average wind speed.

At 8 m/s average wind speed the gap increases further as the larger systems are able to produce permeate at a higher rate. The yearly production for 3 RO systems reaches 112000 m^3 or an average of 306 m^3 per day.

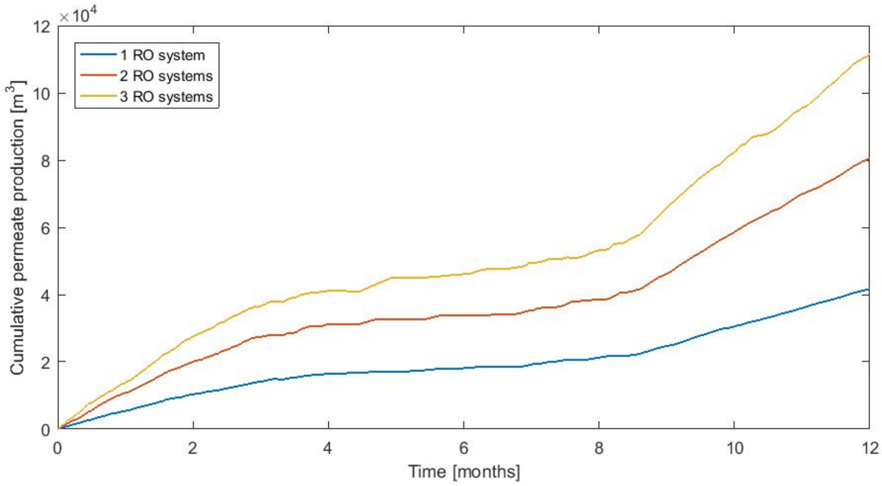


Figure 4.13: Cumulative permeate production of 1, 2 and 3 RO systems coupled to the hydraulic transmission at 8 m/s average wind speed.

From the cumulative production simulation results it can be affirmed that fewer RO systems may be more suited for low average wind speeds as the added value of additional systems may not be worth the investment. At higher wind speeds, however, the difference is more pronounced and may justify the expense of additional motors, pumps and membranes; this will be verified in the financial analysis.

4.4. FINANCIAL ANALYSIS

A financial analysis is performed to make a comparison between the system configurations with different numbers of RO systems. This will be done by calculating on the Levelised Cost of Water (LCoW) and will allow to compare one configuration option relative to another. Levelised cost calculations are often used as a method of comparison of generating electricity by different sources and includes the amortisation of the initial capital cost as well as the return on the invested value and the operation and maintenance costs. In this case the LCoW will allow quantifying the benefit of installing additional RO systems on the Freshwatermill to make use the available wind for water desalination. Whether the overall system will be financially viable in the different configurations will then depend on various factors such as the wind conditions of the location in which the Freshwatermill will be implemented and the cost of alternative water in that location. In addition, the generation of electricity from excess energy should be considered within the financial feasibility analysis. Equation 4.6, describes the calculation of the LCoW.

$$LCoW = \frac{\sum_{t=1}^{T} \frac{I_t + M_t}{(1+r)^r}}{\sum_{t=1}^{T} \frac{W_t}{(1+r)^r}} \tag{4.6}$$

Where I_t are the investment costs in year t, M_t are operation and maintenance costs in year t, W_t is the permeate water produced in year t, r is the discount rate or real interest rate and T is the lifetime of the installation in years.

The investments and maintenance costs per year are presented in the Table 4.2. The initial investments comprise the cost of the windmill; the transmission, which becomes more expensive if more hydraulic pumps are required to be coupled to additional RO pumps (by a factor of 1.2 of the entire hydraulic system); and the maintenance, which comprises a yearly cost for the systems as well as a change of RO membranes for all the RO systems and pretreatment filters which will occur every two years (the maintenance costs are the most expensive case scenarios as it is preferred to obtain a conservative result).

Table 4.2: Capital and maintenance costs and frequency of Freshwatermill with different number of RO systems [10].

Cost [€]	1 RO	2 RO	3 RO	Frequency
Windmill & hydraulic transmission	242000	254000	262000	Year 1 only
General maintenance	10000	10000	10000	Yearly
RO membranes & pre-treatment filters	6000	12000	18000	Every 2 years

A Freshwatermill installation has an expected lifetime of 15 years, although this can be extended with a relatively small cost to refurbish the system. The standard lifetime of 15 years is used to have a more conservative result of LCoW. The discount rate chosen is that of Colombia at 9% as this is an area of interest for the market of the Freshwatermill although the location is not too important as this financial analysis is merely to compare the different Freshwatermill configurations. The yearly permeate production values are obtained from the cumulative permeate productions derived in the dynamic model simulations. These are presented in Table 4.3.

Table 4.3: Yearly permeate production at various wind conditions using different numbers of RO systems.

Average daily permeate production [m^3/day]				
Number of RO systems		**1**	**2**	**3**
Average wind speed [m/s]	**4**	36.7	44.7	43.6
	6	82.0	140.7	186.1
	8	114.2	220.9	305.7

The LCoW values for one, two and three RO systems at average wind speeds of 4, 6 and 8 m/s are presented in table 4.4 and can be more easily compared in Figure 4.14. The average wind speed is highly influential on the LCoW. At low wind speeds additional RO systems do not provide significant increases in permeate production to offset the increase in investment and maintenance costs. From 4 to 6 m/s there is a large drop in LCoW and at this point there is a clear financial benefit in installing two or three RO systems. At 8 m/s the LCoW drops further, though by a lesser amount.

Table 4.4: Levelised cost of water at various wind conditions using different numbers of RO systems.

Levelised cost of water [€/m^3]				
Number of RO systems		**1**	**2**	**3**
Wind speed [m/s]	**4**	3.04	2.78	3.11
	6	1.36	0.88	0.73
	8	0.98	0.56	0.44

4.5. CONCLUSION

The added value of increasing the installed desalination capacity with additional RO systems increases with wind speed. As seen in Figure 4.15, at an average wind speed of 4 m/s the daily permeate production averaged over a year is almost the same whether it comprises one, two or three RO systems. Above 4 m/s additional RO systems give a clear increase in production as they can make use of the higher wind powers. This has a strong influence on the LCoW calculations. In fact, based on the estimated LCoW it can be stated that in a location where the average wind speed is above 4 m/s more RO systems would be financially advantageous. To obtain a more accurate estimate of the LCoW it would be best to use wind data of multiple years, rather than only one, to average out variances between several years.

In the parallel configuration of multiple RO systems the use of valves is vital, as is the control system that governs their functioning. In the computer simulation the control strategy was to switch an additional RO system on when the starting torque was sufficient. If the wind oscillates around a switching threshold the membranes could be damaged by continuous switching. Therefore, the control system for the Freshwatermill

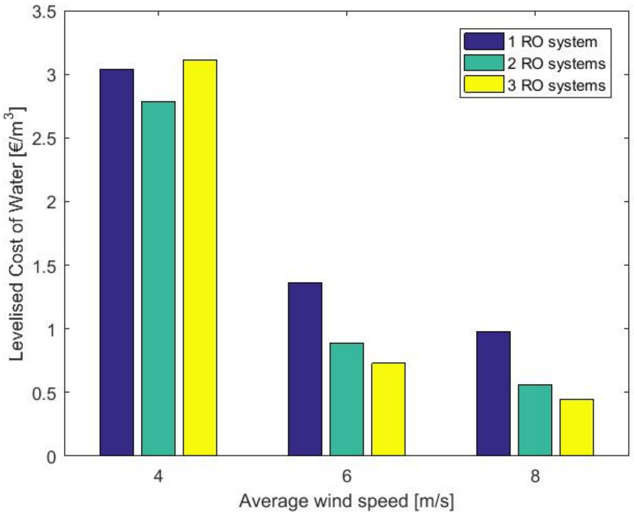


Figure 4.14: Levelised Cost of Water for all tested RO installed capacities at different average wind speeds.

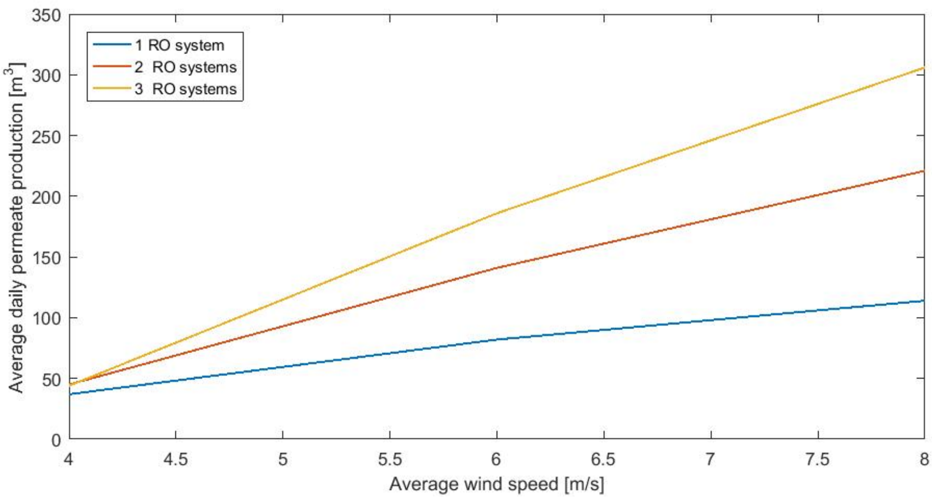


Figure 4.15: Average daily permeate production for all tested RO installed capacities at different average wind speeds.

should include a lag compensator or low-pass filter to ensure that there is a delay in valve switching after the starting torque passes the threshold or that the low-pass filter oscillations.

5

General Conclusions and Recommendations

Throughout this thesis project the development of the Freshwatermill took place in several steps, focussing on the conformation and size of the reverse osmosis system as well as the behaviour of the system while in operation, with the main objective of exploiting the available fluctuating wind power to maximise the production of fresh water. The main objective branched into three sub-objectives which were tackled via the separate steps of experimental test and model simulation.

5.1. Conclusions

Based on a review of RO technologies and on the premise that the fluctuating power supply from the windmill will reach a maximum value in the region of 100 kW, some of the main components of the RO system were selected. This included an axial piston pump and motor unit to serve as HPP and ERD. These components were chosen for several positive characteristics:

- they are made of seawater resistant material which will provide reliability and a long lifetime;
- the combination of the fixed displacement pump and motor offer a simple method of regulating the recovery ratio;
- the versatility in variable operation offered by the positive displacement characteristics;
- the rated capacity of the unit, although too small for the rated power of the windmill, is the most suited compared to other positive displacement options;
- and the high efficiency of the unit.

The first sub-objective was to test the components selected for the RO system for their behaviour. This was done via a static test in which the feed pressure, permeate production and permeate TDS were plotted against the power supplied to the HPP for operation with only one and two pressure vessel units. These static values can be related to a wind speed once the power curve of the hydraulic transmission are available. The results also showed that the operating range with two units was able to cover the range of a single vessel and more, while maintaining the permeate TDS in an acceptable range. Furthermore, the power consumption with two units was lower than with a single unit over the same range. This partly answers the second sub-objective.

The second sub-objective was to evaluate the strategy of unit switching for widening the operational window of the RO system. A dynamic test repeated at various wind speeds showed that unit switching surprisingly did not increase the cumulative permeate production and neither did it significantly lower the TDS level in the permeate. The energy consumption was in fact lower for operation with two fixed units. Consequently the unit switching strategy was rejected and the RO system design was defined with two fixed units which would ultimately simplify the system, making it cheaper and more robust, as unit switching would have required automated valves and a dedicated control system.

Finally, the third sub-objective was that of scaling up the solution obtained in the experimental test using computer model simulation. The model was built to match the components selected for the test and the RO system with two units. The accuracy of the model was verified by comparison with the experimental test results which showed a slight mismatch in power consumption, although it was considered acceptable for its purpose. Dynamic simulations were performed to test different numbers of RO systems connected to the hydraulic transmission. It was established that the windmill could provide sufficient power to supply a maximum of three RO systems, after which the required torque would be too high to start the RO system. It was decided that each RO pump should be coupled to the hydraulic transmission in parallel with automated valves to isolate the coupling motor, allowing to switch each system on or off independently depending on the available power. With a year worth of wind speed data the simulations showed that above an average wind speed of 4 m/s the more RO systems were coupled, the larger the volume of permeate produced. The levelised cost of water of each size of system was then calculated and compared to verify whether the increased permeate production was worth the additional up-scaling investment. Above 4 m/s average wind speed the larger the RO capacity, the lower the cost of water, confirming that the maximum number of RO systems would be the most advantageous. Ultimately, the decision of how many RO systems to install should be location specific, according to the local wind characteristics, maintenance costs, discount rate and value of water.

5.2. Recommendations

Additional simulations could be performed to test the effect of various parameters such as feed water temperature, TDS level as well as different types of membranes. This would provide an insight of the water production capabilities in a range of conditions and situations, making the simulations more locations specific. In order to do this new simulations should be run on ROSA, or similar software, to obtain permeate production data which then needs to be loaded into the Simulink model. This can be tedious and time consuming, which is why an attempt was originally made to reproduce the ROSA calculations method and integrate it into the Simulink model. Due to the mismatch of results with ROSA, most likely due to inaccurately calculated concentration polarisation values, this method was abandoned. Further work on this method would be recommended as applying it to the Simulink model would increase its versatility and user friendliness. Ultimately the model could be applied as a tool for estimating permeate production for a given location.

The focus of this project was on the design of aspects regarding RO system of the Freshwatermill. The electrical generator which will be installed in series to the RO systems on the hydraulic transmission may play an important role in managing the power that goes to the RO pumps. Depending on location requirements the load on the generator can be increased, up to its rated capacity, which would increase its torque and thus the power that it absorbs from the windmill. In this way the power can be managed between desalination and generation of electricity via a control system. Such control system could also manage the automation of the valves that isolate RO coupling motors when power fluctuates. Furthermore, a control strategy is also required to minimise the requirement for membrane flushing after periods of inactivity. This can occur when the wind speed is low and only one of the two or three RO systems is operational. The control method could allow to periodically cycle between RO systems when they are not all operational so that they are not switched off for too long.

As the power curve of the windmill and hydraulic transmission is not yet available, both the experimental test and model simulation results were related to wind speed based on a power curve derived from the original electrical power curve of the Lagerwey 18/80 turbine. The efficiency of the hydraulic transmission the simulation model was estimated with a fixed value of 95%. The new hydraulic transmission power curve is in the process of being measured and could not be included in this project due to time limitations. It would be an important future step to include this data in the model, as soon as available, in order to obtain results that are more representative of the future Freshwatermill's actual potential. The new power curve will be measured in terms of rotational speed and torque. This is important as power may be distributed differently over the range of speeds to the electrical power curve, possibly shifting the distribution of rotational speeds to different wind powers.

Literature shows that there have been studies on RO membranes tested in variable flow conditions [6] although it is recommended to perform practical tests using the actual membranes that will be used for the Freshwatermill. Long term tests would allow estimating their lifetime more accurately. This is because the membranes are not designed to operate at such variable conditions and reaching such low permeate fluxes can deteriorate their lifetime as a result of fouling. Although the DOW FILMTEC SW30XHR–440i 8"×40" membranes seemed promising for the application, every membrane has different characteristics an performances, therefore similar sized and specified membranes of a different manufacturer may also be suitable although with a slightly different performance.

A

APPENDIX A

A.1. LOW SPEED SHAFT POWER CURVE

Without the power curve of the windmill and hydraulic transmission at hand for the preliminary sizing of the RO system, the experimental test and the simulation model, the low speed shaft power curve was derived from the electrical power curve of the original wind turbine and used instead. This is done because hydraulic transmission is claimed to have a higher efficiency than the gearbox and generator although it is first of all important to understand the full potential of the wind turbine rotor.

To calculate the low speed shaft power is estimated based on the nominal torque. The Lagerwey 18/80 specifications presented in Table A.1 define a nominal torque of 8050 Nm. This is therefore taken as the maximum allowed torque on the low speed shaft. The speed of the low rotor at, and below, rated power is calculated the tip-speed-ratio (λ) given n equation A.1, with the rated wind speed and rotor diameter given in the specifications.

$$\lambda = \frac{\omega R_r}{U} \tag{A.1}$$

Where ω is the rotational speed of the rotor and low speed shaft in rad/s, R_r is the rotor radius and U is the wind speed.

Table A.1: Specifications of Lagerwey 18/80 wind turbine.

Parameter		**Value**
Rotor diameter	[m]	18
Number of blades	[-]	2
Nominal power	[kWe]	80
Cut-in wind speed	[m/s]	3
Rated wind speed	[m/s]	12.5
Cut-out wind speed	[m/s]	25
Survival wind speed	[m/s]	60
Rotor minimum speed	[rpm]	50
Rotor maximum speed	[rpm]	120
Rotor speed control	Full span pitch, by mechanical passive pitching	

Therefore, the low speed rated power was recalculated to equal the product of the rotor speed at rated power and the rated torque (as in equation 4.4). The efficiency of the gearbox and generator is then calculated by dividing the reted electrical power of 80 kW by the newly calculated low speed shaft power of 103 kW. The same efficiency is used to calculate the rest of the low speed shaft powers below the rated torque. Although the gearbox and generator efficiencies would not be constant over the range of speeds, this assumption is deemed acceptable to estimate the low speed shaft power.

The electrical power curve and the low speed shaft power and torque curves are plotted in Figure A.1.

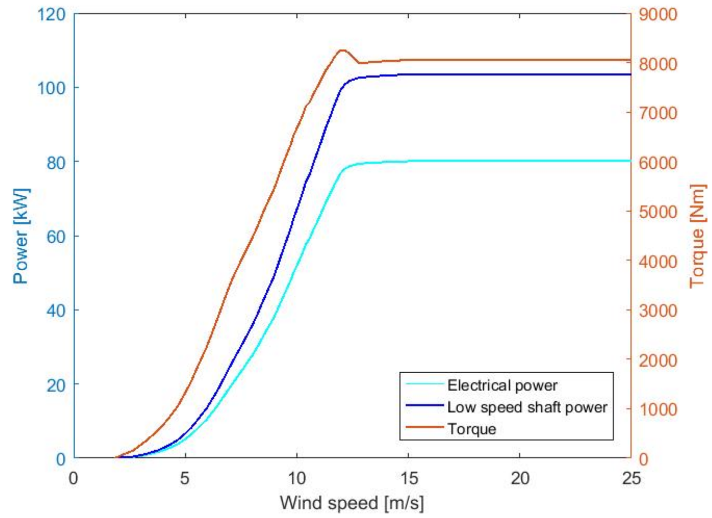


Figure A.1: Electrical power curve and estimated low speed shaft power and torque curves.

The overall power coefficient which only represents aerodynamic efficiency, C_p, is also calculated as in equation A.2 and plotted with the electrical power coefficient which includes the gearbox and generator efficiencies, C_e, obtained from the wind turbine specification data.

$$C_p = \frac{P}{1/2\rho A U^3} \tag{A.2}$$

Where P is the shaft power, ρ is the air density and A is the rotor's swept area.

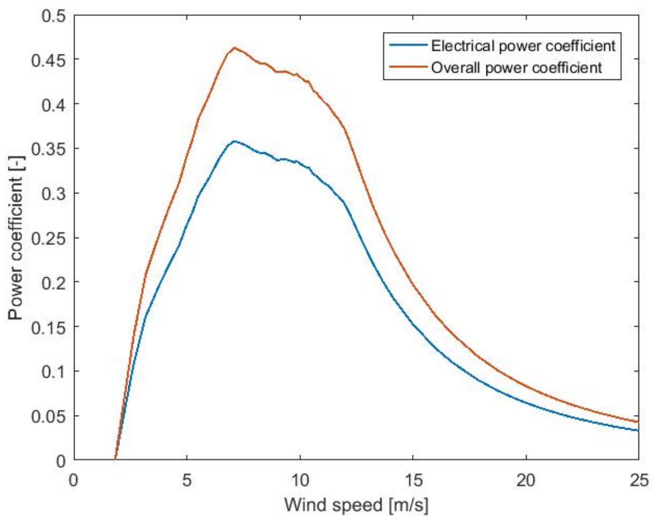


Figure A.2: Electrical and overall calculated power coefficient curves.

B

Appendix B

In the following pages the specification sheets of the RO membrane elements selected for this project are presented, as well as the HPP and ERD specification sheets which show the curves that relate pressure, power, torque and flow, from which the equations used in the computer model are derived.

Product Data Sheet

DOW FILMTEC™ SW30XHR–440i Element

Seawater Reverse Osmosis Element with *iLEC*™ Interlocking Endcaps

Description

Dow Water & Process Solutions offers various premium seawater reverse osmosis (RO) elements designed to produce high quality water which may reduce capital and operation costs of desalination systems. DOW FILMTEC™ Elements combine excellent membrane quality with automated precision fabrication to take system performance to exceptional levels.

DOW FILMTEC™ SW30XHR–440i Element are the highest rejection seawater RO elements in the DOW FILMTEC element portfolio, enabling stringent water quality requirements to be met reliably with single-pass seawater systems in most situations. In addition, the combination of highest active area and a thick feed spacer results in higher productivity and lower cleaning frequency which enable sustainable lower lifecycle cost. Benefits of the DOW FILMTEC SW30XHR–440i element include:

- Highest NaCl and boron rejection to help meet World Health Organization (WHO) and other drinking water standards more cost effectively.
- The highest guaranteed active area of 440 ft^2 (41 m^2) permits lowest system cost by maximizing productivity and enables accurate and predictable system design and operating flux.
- The combination of highest active area with a thick feed spacer (28 mil) allows low cleaning frequency and high cleaning efficiency.
- Utilization of the distinct *iLEC*™ Interlocking Endcaps helps reduce system operating costs and reduce the risk of O-ring leaks that can cause poor water quality (see Form No. 609-00446 for information on the cost-saving benefits).
- Sustainable high performance over the operating lifetime, because oxidative treatments are not used in membrane production. This is one reason DOW FILMTEC elements are more durable and may be cleaned more effectively over a wider pH range (1 – 13) than most other RO elements, which use oxidative treatments.
- Effective use in permeate staged seawater desalination systems without impairing the performance of the downstream stage.

Product Type

Spiral-wound element with polyamide thin-film composite membrane

Form No. 609-03002, Rev. 1
October 2015

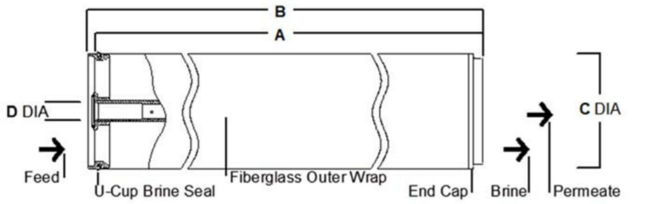
Figure B.1: Specification sheet of DOW FILMTEC SW30XHR–440i 8"×40" membrane elements (page 1).

Product Specifications

DOW FILMTEC™ Element	Active Area (ft²)	Active Area (m²)	Feed Spacer Thickness (mil)	Permeate Flow Rate (GPD)	Permeate Flow Rate (m³/d)	Stabilized Boron Rejection (%)	Stabilized Salt Rejection (%)
SW30XHR–440i	440	41	28	6,600	25	93	99.82

1. The above benchmark values are based on the following test conditions: 32,000 ppm NaCl, 800 psi (5.5 MPa), 77°F (25°C), pH 8 and 8% recovery.
2. Permeate flows for individual elements may vary ± 20%.
3. Minimum Salt Rejection is 99.7%
4. Stabilized salt rejection is generally achieved within 24 – 48 hours of continuous use; depending upon feedwater characteristics and operating conditions.
5. Product specifications may vary slightly as improvements are implemented.
6. Active area guaranteed ±5 %. Active area as stated by Dow Water & Process Solutions is not comparable to the nominal membrane area figure often stated by some element suppliers. Measurement method described in Form No. 609-00434.

Element Dimensions



DOW FILMTEC™ Element	A (in.)	A (mm)	B (in.)	B (mm)	C (in.)	C (mm)	D (in.)	D (mm)
SW30XHR–440i	40.0	1,016	40.5	1,029	7.9	201	1.125 ID	29 ID

1. Refer to Dow Water & Process Solutions Design Guidelines for multiple-element applications. 1 inch = 25.4 mm
2. Element to fit nominal 8-inch (203-mm) I.D. pressure vessel.
3. Individual elements with *iLEC*™ Interlocking Endcaps measure 40.5 inches (1,029 mm) in length (B). The net length (A) of the elements when connected is 40.0 inches (1,016 mm).

Operating and Cleaning Limits

Maximum Operating Temperature [a]	113°F (45°C)
Maximum Operating Pressure	1,200 psig (83 bar)
Maximum Element Pressure Drop	13 psig (0.9 bar)
pH Range, Continuous Operation [a]	2 – 11
pH Range, Short-Term Cleaning (30 min.) [b]	1 – 13
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance [c]	< 0.1 ppm

[a] Maximum temperature for continuous operation above pH 10 is 95°F (35°C).
[b] Refer to guidelines in "Cleaning Procedures" for more information.
[c] Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, Dow Water & Process Solutions recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin "Dechlorinating Feedwater" for more information.

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Figure B.2: Specification sheet of DOW FILMTEC SW30XHR–440i 8"×40" membrane elements (page 2).

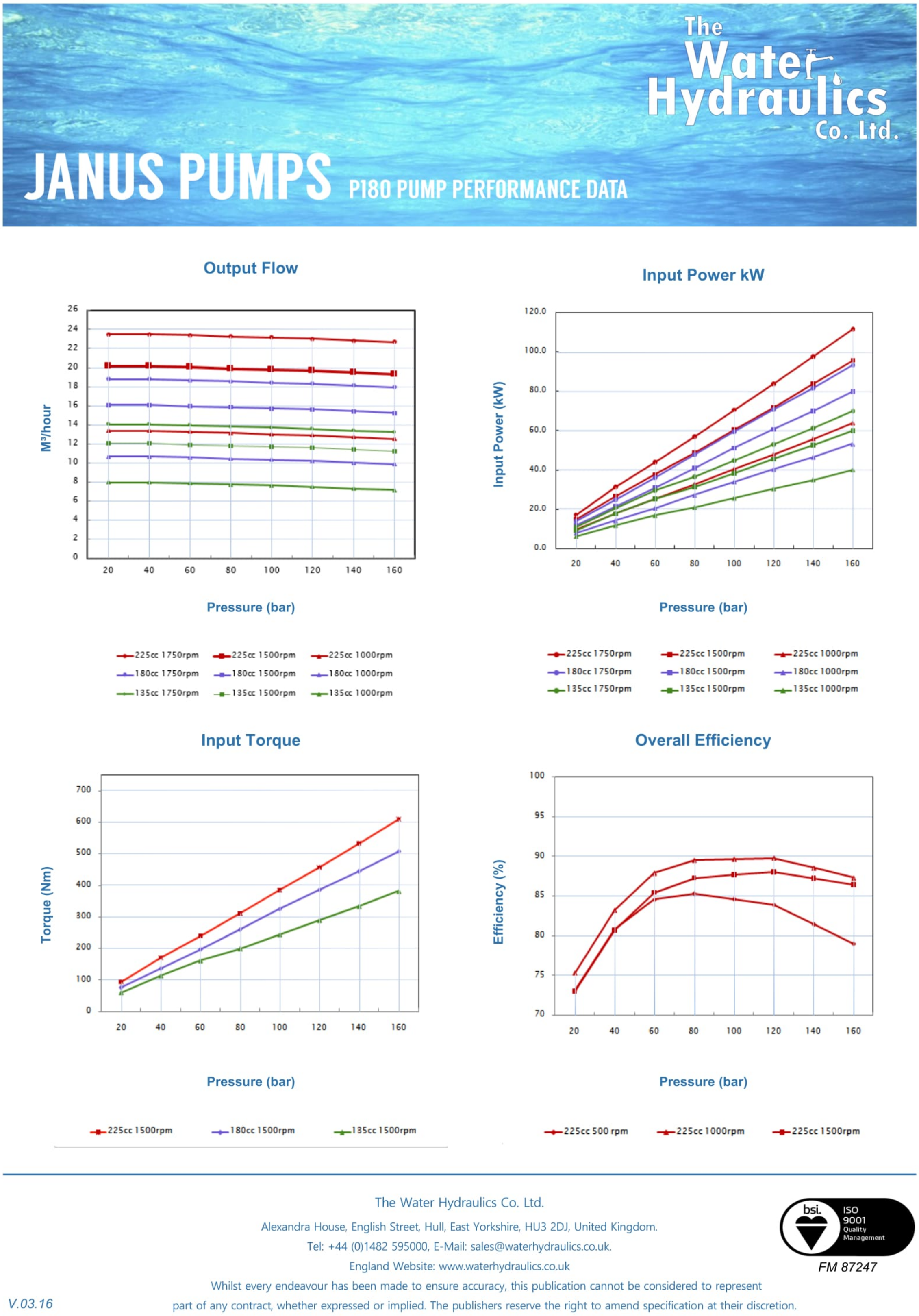

Figure B.3: Specification sheet with of the axial piston pump used as the HPP.

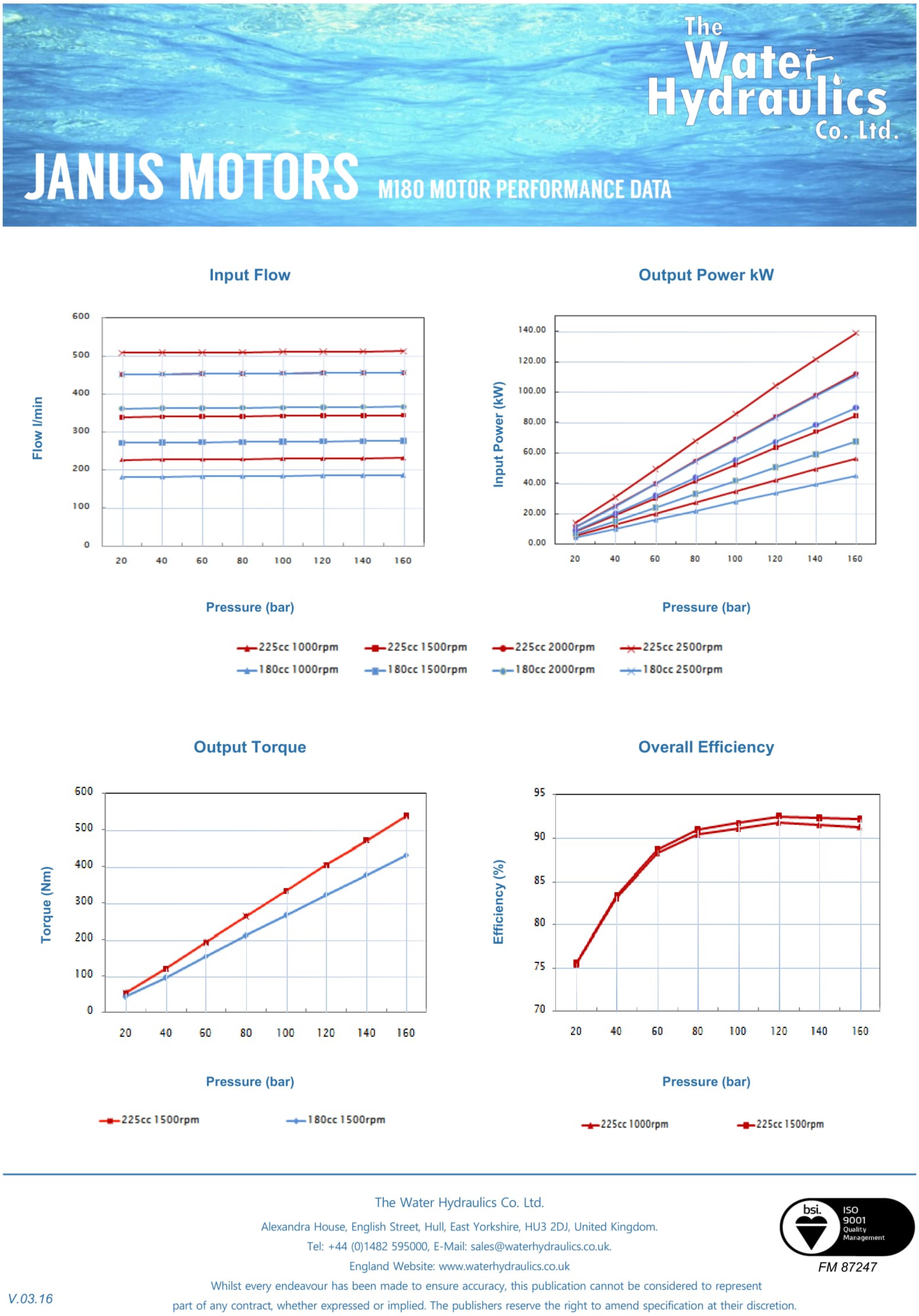

Figure B.4: Specification sheet with of the axial piston motor used as the ERD.

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