Analysis of the utilisation of renewable energy for remote small – scale desalination

by

Vincent Farrell

A Thesis Presented for the Degree of Master of Science in
Energy Systems and the Environment

Energy Systems Research Unit
University of Strathclyde
September 2003

COPYRIGHT DECLARATION

Acknowledgements

I would like to thank Mr. Craig McLean for supervising my project and for his general advice, Prof. Joe Clarke for his patience, Mr. G.G. Pique (of Energy Recovery Inc.) and Mr. Mike Baker (of RAM pumps) for giving me both information and advice, Mr. Ben Sampson for giving me information on Lundy Island, Dr. Brian Stimpson for giving me another chance, and to my parents for their love and support.

Contents

Section Three – Systems Analysis 42

List of Figures

Abstract

The notion of utilising renewable energy to power desalination plants is not a new one, however this field has remained relatively dormant. In recent times the increased maturity of renewable technologies has been largely responsible for a greater awareness of this particular topic.

Common analysis techniques seem to focus on medium to large – scale requirements and do not deal with the problems of small – scale desalination. Here we have analysed the most common small – scale scenario – water for remote regions – and attempted to build a foundation for further research into this area. We have also looked at the problems with selecting and then implementing a suitable renewable technology and discussed the problems associated with intermittent supply (we found that some of the problems with renewable energy are site specific but in the main inherent difficulties still plague possible future designs).

We have devised two selection tools which are solely concerned with tackling the aforementioned problems, they are dedicated to the solitary purpose of analysing and solving the difficulties associated with selecting a desalination method for a remote region and as such are more powerful than other commonly found selection techniques.

In order to show how these tools should be implemented we have developed a case study to act as an exemplar. The case study is of Lundy Island (a small island in the approaches to the Bristol Channel and some twenty kilometres west of the Devon coast) and we have endeavoured to complete as comprehensive an analysis as possible. The results of the case study highlighted the most important design factors of any remote desalination scheme – reliability and maintenance.

These results are more than likely to be representative of all remote regions and therefore must be considered during any such design process.

Section One

Analysis of the Problem

1.1 Introduction

The process of prescribing a desalination method to a remote region is widely accepted to be a most problematic area. This particular area of desalination has suffered from very little development, primarily due to its generally financially unattractive nature. In cases where small-scale desalination processes have been utilised in remote areas, the capital costs are such that it takes a great deal of time for the plant to "earn its worth" and to those who must foot the bill this is an unappetising proposition.

Recent years however have been witness to an increased awareness and interest in the difficulties presented by small-scale desalination. This is a direct consequence of falling process costs that come with the refining of the technology and general operational experience [1].

Despite the important work that has been performed in this field it is somewhat ironic when we consider that the very definition of what constitutes "small-scale" still remains unclear [2]. Of course in a case such as this the context of the problem plays an important role, it is clear that "small-scale industrial" desalination and "small-scale remote region" desalination are going to suggest two very different things.

The selection techniques used to determine the desalination process best suited to certain predefined parameters are also hindered by this vicissitude, therefore the current selection processes used are unreliable when used to consider the domain of small-scale desalination.

It seems quite natural that in this day and age we should consider utilising the potential of renewable energy sources (RES) to power such energy intensive processes. Indeed in most cases fresh water scarcity coexists with abundant renewable energy potential [3], so the two go hand in hand with one another. In ideal scenarios this would indeed be the case, yet the practice of combining renewable technology with desalination technologies still presents many difficulties. The main difficulty found with such set-ups is the lack of a suitable selection tool in order to determine the renewable source with the greatest potential at any given site. As a consequence of the inherent difficulties in selecting an appropriate RES-desalination combination we are finding that this unique field is being, for the most part, ignored.

It would appear that integrating renewable energy sources into small-scale desalination for remote regions is just a conglomeration of a multitude of problems. Nevertheless present work in this particular area has shown the potential for continued development. As a result of the need for further investigation into this field it is the aim of this thesis to focus solely on the distinctive problems presented by this specific topic. Here we shall further explore the technical and philosophical aspects that are present when designing a renewable powered desalination system for a remote community. The inclusion of a case study will give some idea of just how demanding this process actually is.

References

1. & 3. Voivontas, D et al: "*A tool for the design of desalination plants powered by renewable energies* ", Desalination 133 (2001), 175 – 198.

2. Ayoub, J and Alward, R: *"Water requirements and remote arid areas: the need for small-scale desalination",* Desalination 107 (1996), 131 – 147.

1.2 Method of Analysis

There are two conventional approaches that nearly all desalination experts agree on when comparing the various desalination methods: performance comparison and cost comparison [1]. In performance comparison technical evaluations are applied to assess the ease of operation, the level of process complexity (number of controls, required skills of operating personnel) and maintenance requirements. However such a comparison is subjective and useful results can be difficult to achieve. The process is hampered by the fact that none of the processes should be difficult to operate and general comparisons between various desalination processes are problematic because each process has its own optimal parameters of operation. It is here that a useful selection tool comes to the fore, by linking the geographical and environmental attributes of any given area to the individual benefits afforded by certain desalination technologies.

The first half of the analysis aims to tackle the development of suitable selection methods by exploring conventional techniques and highlighting the areas under which there is room for improvement. The alterations of existing approaches have the purpose of creating a truly dedicated small-scale desalination selection tool. If we are then to also consider the possibility of integrating renewable energy then it is necessary to adopt a similar process of investigation. However now the aim is to ensure that these two selection tools are interdependent, as autonomous operation will result in an inefficient selection process. To qualify the selection tools a case study will be shown whereby one will have a better idea of how to implement these tools.

As will be stated many times throughout this thesis, the selection processes only perform a semi-quantitative evaluation and once its recommendations have been made it is then “up to us” to perform a far more in-depth examination of the available options.

Once the selection phase has been completed it is then necessary to investigate these choices. Rather than just recommend this as what one should do the second part of the thesis presents a full technical exploration of the assessments made for our case study. Without a shadow of doubt this a far more intensive process but one that is crucial in the final evaluation.

The above processes are inextricably linked and at all times one must endeavour to keep an open mind, a option recommended by the selection tool may, under closer inspection, be found to be in some respects deficient and as such incompatible with regards to the parameters of our study.

1.3 Case study parameters

The case study will deal with Lundy Island, a small island in the approaches to the Bristol Channel and some twenty kilometres west of the Devon coast. The UK is most definitely not the type of place that is normally associated with the need for desalination but this small island seems to fit the bill in so many ways.

Figure 1: Aerial view of Lundy Island

Most are aware of the climate change issues that are affecting the world in which we live and unfortunately the UK is also falling prey to these changes. The Island of Lundy recently became a victim of these affects when in the summers of 2001 and 2002 it suffered from rather serious water shortages [1]. Traditionally the Island employs rainwater harvesting to supply its water requirements, however during these particular summers most of the rainfall in the Bristol Channel area missed the island. The island is a very small one (three and a half miles by half a mile long) this therefore means that even under the best circumstances it cannot capture a lot of water. This problem came at height of the tourist season and the influx of visitors had swelled the island’s population from twenty-five to upwards of eighty. The island does have a fifty thousand gallon holding tank, but under typical western world consumption levels of one hundred and eighty-one litres per person for each day [2] this would only last for two weeks during the summer. To overcome this problem the locals (and visitors) faced severe water restrictions eventually reducing the islands consumption to a mere two thousand gallons a day whilst water was eventually shipped in from the mainland (although this was in small quantities it nonetheless provided some relief).

As a result of the warmer summers and the reduced summer rainfall, when obviously we have a situation where demand is rising and supply is falling [3], Lundy is threatened with this becoming a more regular problem (Lundy, however is not the only island to have suffered from a drought - this crisis also occurred in Tiree and Coll during the summer of 2000). The consideration of a place such as Lundy for the utilisation of desalination indicates that we can no longer think of the water shortage problem as one that is solely associated with the hot, arid regions of the world.

To examine the potential of erecting a small desalination plant on Lundy it is necessary to examine some areas, which could have an affect upon any system design.

Potential for Renewable Technology

When examining a potential site it is necessary to study the potential for establishing a renewable energy infrastructure (the reason why will become clear later). In this instance however we found that Lundy is already making use of a 55kW wind turbine (alongside a diesel generator). It is quite a basic system but nonetheless it is claimed that the energy provided by the wind provides around seventy percent of the island's needs.

Local Environment

Lundy's flora and fauna is so rich an diverse that most of the Island is a Site of Special Interest and the seas surrounding it are England's only statutory Marine Nature Reserve. The future well being of the species and habitats within the reserve largely depend upon the ability to deal with the potential threats to them. This clearly indicates that any system established on the island must be as non-invasive as possible. This however is easier said than done. The seawater temperature is also

an important variable used in the technical evaluation of desalination processes. In summer the temperature is on average around 15 degrees Celsius and during the winter it is 7 degrees Celsius [4]. The absence of brackish waters on the island suggest that any desalination system will use seawater as its feed source.
The determination of the regions parameters helps the selection and technical processes, thus allowing for more accurate answers.

Another requirement we must bear in mind is the quality of the water required; Lundy requires potable water (which means its fit for human consumption) this must have a salinity of less than 500 ppm (parts per million). Any desalination process we analyse must be capable of producing such quality water.

References

1. www.bbc.co.uk/news
2. www.environment.sa.gov.au/reporting/human/water.html
3. www.ukcip.org.uk/pdfs/SW_2 Our Changing Climate.pdf
4. www.defra.gov.uk/environment/marine/quality/index.htm

Section Two

Development of Selection Tools

2.1 The parameters of small-scale desalination

Contrasted to large-scale desalination systems where optimisation of energy costs and plant performance are major factors in the selection of desalination technology, the selection and design of small-scale systems is often based on a combination of climatological, technical, physical, social and economic factors prevalent in the intended location [1]. A conventional desalination system is generally large-scale, high technology, high efficiency and high pressure, requiring regular technical control and servicing. The design of the system fulfilling the remote area criteria depends upon sacrificing high efficiency in terms of lower recovery ratios, but with the benefits of lower total energy input requirements [2]. The adaptation of desalination systems to remote community use, where maintenance facilities are generally not available, is largely a question of system design. In order to make the selection and design process as efficient as possible we must aim, when possible, to conform to the following factors [3] :-

- Capital and running cost which is affordable by small communities and comparable with the cost of water delivery of alternatives such as rainwater harvesting

- Automatic operating system, with start-up and shutdown as demand requires. It should be designed to shut down in case of malfunction, thus limiting damage to system components.

- Low power requirements, preferably using renewable energy pumping systems, given the lack of available reliable power on site.

- Realise that operation and maintenance will be performed by relatively low skilled staff.

When one is making use of the following selection tool it is important to consider the above factors, it is these parameters that allow us to differentiate the small-scale selection process from all others and as we shall see this is vitally important. Ultimately the goal of the small-scale selection tool is to allow the individual assessment of any remote community whilst reminding the user that he/she must abide by certain design factors.

References

1. Ayoub, J and Alward, R: *“Water requirements and remote arid areas: the need for small-scale desalination”,* Desalination 107 (1996), 131 – 147.

2. & 3. Robinson, R et al: *“Development of a low-cost reverse osmosis desalination unit for remote communities”*, Desalination 86 (1992), 9 – 26.

2.2 Selection tool for small-scale desalination

The goal of any effective selection method is to save time and resources by examining candidate solutions and suggesting those, which optimally satisfy our predefined aims. The idea of employing a technical evaluation process to ascertain which desalination technology is best suited to meet certain parameters is by no means a new one. This, and the also next, section will act as a way of determining the renewable energy (RE)-desalination combination for any small-scale site.

It has been the goal of this project to alter current selection techniques to deal with, and only with, small-scale desalination. Although this set-up will be used here to assess the needs of Lundy Island it is hoped that it will also act as a schematic for examining all other small-scale desalination programs where the ultimate goal is the integration of a renewable energy source.

As noted above no real attempt has been made to implement a systematic selection program dealing with small-scale desalination, one may say that with the numerous selection tools currently present surely they must leave very little room for improvement, but this is not the case. Careful research into this particular field has found that current evaluation methods are inherently flawed and different variables must be investigated when one considers any small-scale desalination problem.

The main problem with present evaluation techniques is that they aim to examine the entire gamut of possible scenarios, and as a consequence they can only return limited conclusions. For instance when discussing criteria such as operational flexibility and maximum size of installations one finds that MVC is considered deficient in these areas. However, if we investigate the parameters of the problem, i.e. location and water requirements, we find that in the field of small-scale desalination the aforementioned factors do not present themselves as real barriers. Every small-scale desalination system has to be uniquely designed within the context of the physical, social and financial parameters of the particular communities they intend to serve. As a result what may be assessed economical or practical in one location may not be applicable in another. Here we have sought to solely examine the needs of small-scale desalination and as a result it is a far more useful selection tool and allows the user to avoid the extra work required for the more traditional selection methods.

In view of such flaws a revised system has been designed incorporating some of the finer points of small-scale desalination. However, before we can proceed we must state the assumptions upon which we define small-scale desalination for remote regions.

- Product capacity no greater than 30 cubic metres a day, equivalent to one hundred and fifty people (based on typical consumption levels of 181 litres per day per person)

- Proposed site will be a sufficient distance away to prevent grid connection. Therefore it more than likely that the community of the proposed site will probably making use of a diesel engine supply system (if indeed they have a supply at all).

- Operation and maintenance will be performed by relatively low skilled staff (therefore increased reliability is a must)

- Feed water will be either seawater or brackish water. Establishing what type of water is going to be used as our feed source is very significant. This is because the degree of salinity in the feed water can directly affect the energy consumption of a particular process (some processes cannot even function under certain feed water conditions). The level of dissolved salts present in seawater is 35000mg/l [1] and brackish water (3000 mg/l [2]). Thus seawater will lead to a more energy intensive process.

If a desalination project fits these basic assumptions then the following procedure will be of use to it. The evaluation method is based upon nine common factors that are common to all desalination technologies [3]. These factors will be found in almost any respectable selection process, however here we will look at them solely in the context of small-scale remote region desalination and take into consideration the four factors mentioned in section 3.1.

- A = excellent compliance with criterion
- B = good compliance with criterion
- C = poor compliance with criterion

The nine factors are:-

1. Process maturity

Examines if the processes have been available commercially for a number of years and have an established technical history. Processes that are still in experimental or development stages, and not yet commercially available are, therefore, excluded from further consideration. In this instance processes which have a history of being utilised in small-scale situations should be considered first. Processes are rated A for mature processes with many applications, and C for experimental processes.

2. Complexity of operation

This refers to the level of operational and control input that is required for proper operation of the process. In cases such as ours, where remote regions are likely to utilise renewable energy for desalination, it is clear that this complexity level must be relatively low. An important aspect is whether automated operation is possible as clearly this removes considerable burden from the regions engineer. Non-complex and easy to control process, rated A.

3. Flexibility of operation

In view of the fact that RE is by nature variable and intermittent, it is important that we recognise such variations in the design process. This means that the operation of the process combination should be flexible to cater for variable energy input or, a provision should be made for some type of energy storage. More often than not this variable will have a financial consequence upon our final evaluation as not all desalination processes can operate under intermittent energy conditions. Flexible operation, rated A.

4. Energy requirements

The energy efficiency of the process is an important consideration in process selection. Minimum energy input for maximum product output from seawater or brackish water plays an important role in process selection and in product water costs. It is clear however that this factor is not as important due to fact that we intend not to use fossil fuels (however it still plays a significant role). Low energy requirements, rated A.

5. Water recovery

The water recovery together with energy consumption and capital costs are the main cost factors in desalination. Water recovery should therefore be as high as possible within the constraints of scaling, fouling and corrosion of equipment. As previously mentioned we can expect to find lower recovery rates than we would in larger scale plants, but unfortunately this is unavoidable. High recovery, rated A.

6. Pre-treatment requirements

These requirements depend on the feed water quality and the effectiveness of the desalination process. Pre-treatment requirements may be more stringent or less stringent depending on the process and therefore they affect the complexity and cost of operation. In the case of methods that make use of fairly high chemical pre-treatment it will be necessary to consider the impact upon the local environment. Thus if we have a site which has certain wildlife reserves, or such like, it is evident that the expulsion of chemical wastewater is unfavourable. Low pre-treatment requirements, rated A.

7. Product water quality

The product water quality (and use) determines the post-treatment requirements of the water. Distillation processes normally produce water with very low levels of dissolved solids (<50 mg/L), i.e. highly corrosive and not suitable for long-term consumption. The product water must therefore be re-mineralised (stabilised) before distribution. The mineral content in product water from membrane processes is normally much higher and no re-mineralisation is required. The product water must also be free of any harmful micro-organisms or other harmful substances. Low post-treatment requirements, rated 3.

8. Maintenance requirements

Proper maintenance of a desalination plant and its ancillary equipment is very important to ensure maximum availability of the plant and therefore maximum production and minimum costs per m3 [3]. This requirement becomes of even greater importance in the case of renewable energy applications in remote or isolated areas. If extensive or high-level maintenance is required the possibility of neglect or improper maintenance becomes greater and, therefore, also the possibility that the plant may be non-operational for long periods.

Maintenance requirements depend on the nature of the process, the design and specification of equipment, and the operating conditions. Special designs and special equipment to reduce maintenance requirements will add to the capital costs but should result in increased output from the plant. Low maintenance requirements, rated 3.

9. Waste Products

The wastes from a desalination application consist mainly of the concentrate (usually brine) from the desalination plant together with wastes from the pre-treatment processes such as sludge from chemical precipitation. We briefly discussed in six the possible environmental problems stemming from such wastes therefore; provision must be made for proper disposal of such wastes, which also adds to the total costs. Minimum waste products, rated 3.

These are the nine parameters which one must consider when selecting a method of desalination. At this stage it is not imperative to go into considerable depth for each desalination process that you intend to analyse, all you require are general assumptions about the technology and a good understanding of the region of intended application.

One must remember that this is a process of selection not by any means a final evaluation. Technologies highlighted using this selection method may under closer technical and economic scrutiny be found to be wholly unsuitable for the required task. As we have stated before the aim of this entire project is to provide a case study using these selection tools illustrating how they are merely the start of a very long and complex procedure.

References

1 & 2. Liu, C et al: “Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control”, Desalination, 150 (2002), 277 - 287.

3. Oldach, R: “Matching renewable energy with desalination plants”, Middle East Desalination Research Centre, 2001, 22 – 25.

2.3 Lundy Island case study: Part one

For the case of Lundy Island it was decided to evaluate only three desalination processes – Mechanical Vapour Compression (MVC), Reverse Osmosis (RO), and Electrodialysis (ED). These three techniques are established means of small-scale desalination and so they are to a certain degree easier to analyse.

Again it is important to reiterate the parameters that Lundy Island places on any potential desalination process.

1. Seawater will be used as feed water.

2. Necessary to keep pre-treatment to a minimum.

3. Low energy requirements, the power system on Lundy is not large enough to sustain an inefficient desalination plant.

4. System needs to be easy to operate.

The selection tool is merely a brief analysis of the options at our disposal, if one has a set of requirements that they must adhere to then common sense will more often than not dictate which desalination methods are viable. At this stage of assessment one need not know the ins and outs of a certain method, the selection tool has been arranged so that one may come to general useful conclusions with a limited bank of information. It would clearly defeat the purpose of the selection tool if one had to invest large amounts of time in understanding the operating conditions of a system only to find it was ultimately useless.

The complete analysis is shown below in Figure 2.

Criteria	Reverse Osmosis	MVC	Electrodialysis
Process maturity	Many small-scale plants in operation (A)	Many small-scale plants in operation (A)	Many small-scale plants in operation (A)
Complexity of operation	Operational control is required as membranes are sensitive (B)	Relatively simple operation (A)	Relatively simple operation (A)
Flexibility of operation	Inflexible with regards to intermittent supply (B)	Quite flexible (A)	Inflexible ED cannot process seawater (C)
Energy requirements	Electrical energy requirements are very low for seawater (A)	Quite high energy requirements (B)	N/A
Water recovery	Limited, but good enough for small-scale (A)	Good for small-scale applications (A)	N/A
Pre-treatment requirements	High for seawater feed, could affect local habitat (C)	Some treatment but nothing compared to RO (A)	N/A
Product water quality	Limited post-treatment required (B)	Requires little post-treatment (B)	N/A
Maintenance requirements	High (C)	High (C)	N/A
Waste products	Concentrated brine (C)	Concentrated brine (C)	N/A

Figure 2: Evaluation of desalination system parameters

The results provided by the selection process are rather interesting. It was disappointing to find that ED was incompatible with seawater, as it has very low energy requirements but obviously it is better to discover this now rather than later on. It is also interesting to see that the remaining systems both offer quite complex problems with regards to the environment, however a deeper analysis need to examine to what extent. Whilst RO seems to offer problems with possible pre-treatment requirements it offers on the other hand the prospect of a low energy system, this is a dilemma that needs to be more closely assessed. In the case of Lundy it was decided to that further research be performed on the RO and MVC systems.

2.4 Why use renewable energy?

Conventional desalination is energy intensive. Thus, one of the major concerns to developing water production by desalination is the cost of energy. Apart from the cost implications, there are environmental concerns with regard to the burning of fossil fuels [1]. The amount of energy used in the world for desalination is comparable to the total energy requirement of an industrialised country such as Sweden [2]. This gives an idea of the amount of CO_2 emitted by the desalination industry. Given the current understanding of the greenhouse effect and the importance of carbon dioxide levels in the atmosphere, environmental pollution caused by burning fossil fuel for desalination is a major concern.

Renewable energy sources (RES) represent one promising option for the considerable energy needs of desalination processes, this is especially so when one considers remote regions (such as islands) where the use of conventional energy (fossil fuels) is costly or not available. In most cases fresh water scarcity coexists with abundant RES potential [3]. The coupling of renewable energy sources with desalination processes is seen as having the potential to offer a sustainable route for increasing the supplies of potable water.

However, desalination systems driven by renewable energies are scarce, they only represent about 0.02% of total desalination capacity. It is apparent that this is a very technically immature area but more attention is now being paid.

References

1. & 2. www.desware.net/desa7.aspx

3. Voivontas, D et al: "*A tool for the design of desalination plants powered by renewable energies* ", Desalination 133 (2001), 175 – 198.

2.5 Renewable energy selection process

In an instance such as Lundy, or indeed any remote area where a grid connection is unrealistic, a stand-alone RES powered desalination scheme offers the only probable chance of integrating RES into the desalination process. The main desirable features for these systems are low cost, low maintenance requirements, simple operation and, perhaps most importantly, very high reliability.

The selection process for determining the renewable source best suited to a particular type of desalination process is well trodden [1], and the goals of any assessment procedure remain the same - the selection at any given site of an abundant renewable energy resource capable of delivering suitable energy to some specific desalination process.

Although far less problems are presented than the previous section some subtle alterations to standard selection procedures are still necessary to form a suitable evaluation model, which can best examine the energy needs of a small-scale desalination process. It seems that the current evaluation of RES-desalination combinations suffer from a similar flaw, in that selection methods for both problems are not interdependent. Rather than working hand in hand the two processes are presented as two separate entities disparate from one another. As you shall see an attempt has been made to fully integrate the desalination technology results into the selection of a suitable renewable energy technology.

As before we must thoroughly investigate our area of interest, in this case the potential of a RES at any given site, and go on to develop a database of information based on the important parameters. In this case if we work on the basic premise that renewable energy (RE) resources are site specific then it is indeed imperative to perform a detailed assessment of resources available at that site.

By applying this information, in parallel with the conclusions drawn from the former section, to a simple four-step evaluation program we can ascertain which RE meets our predetermined goals (as mentioned above). The first two steps take into account and analyse the recommendations from the desalination part of our analysis and help to establish the RES that is best suited to provide power for a given desalination method. The third part makes use of the information that should be obtained from our site research (e.g. resource availability, any existing renewable infrastructure, and site requirements). Once these three steps have been completed, a comparison is made between the results of the respective procedures in order to equate what potential the site offers against the energy requirements of our desalination plant. In the event that after this appraisal we still have two (or more) RES that fulfil our needs then a fourth, and final, step acts as a “tie-breaker” in order to resolve this stalemate.

In essence the first step aims to establish the RES options open to our disposal, whereas the remaining three act to eliminate the most superfluous of these options. A more detailed breakdown of each step is provided below discussing exactly how we can apply these principles to small-scale desalination.

1. The examination of power demands for desalination processes

If the selection process for desalination techniques has been properly completed then one will have very good idea of the desalination method that is to be analysed, and should therefore recognise the type of energy (e.g. thermal, mechanical or electrical) required to operate that specific desalination plant. As such one can identify the renewable energy source(s) capable of supplying this type of energy.

For instance, if an RO plant meets the criteria for desalination technology then we should know that only electrical energy will fit the systems power requirements, consequently we must look at the methods employed to generate electricity. Basic research on renewable energy technologies presents that; wind energy, PV (photo-voltaic), tidal, and wave are all capable of meeting this demand.

2. Determining the suitability of renewable energy sources

This is the first of the elimination procedures and looks to investigate the technical maturity (this idea has been discussed in the previous section) of the renewable energy techniques taken from the first step. The point of this is very clear, the more experimental a technique is then the more likely it is to have a high cost attached to it. A method of how to establish which technologies are technically and financially stable (and which aren't) is given in Figure 3**.**

Type of available renewable technologies	Suitability for powering small-scale desalination plants
PV	Suited to plants requiring electrical energy, good match for small-scale
Solar thermal energy	Suited to plants requiring thermal energy, typically a good match for large-scale
Wind Energy	Suited to plants requiring electrical energy, good match for small-scale
Geothermal	Suited to plants requiring thermal energy, typically a good match for large-scale. Resource is very limited
Tidal	Possibly well suited but technology isn't mature enough yet
Wave	Possibly well suited but technology isn't mature enough yet
Hydropower	Possibly well suited but technology isn't mature enough yet

Figure 3: Evaluation of mature renewable technologies

With regards to the small example given in step one we may say that, under our method of evaluation, tidal and wave energy are yet financially viable methods of energy production under our given circumstances.

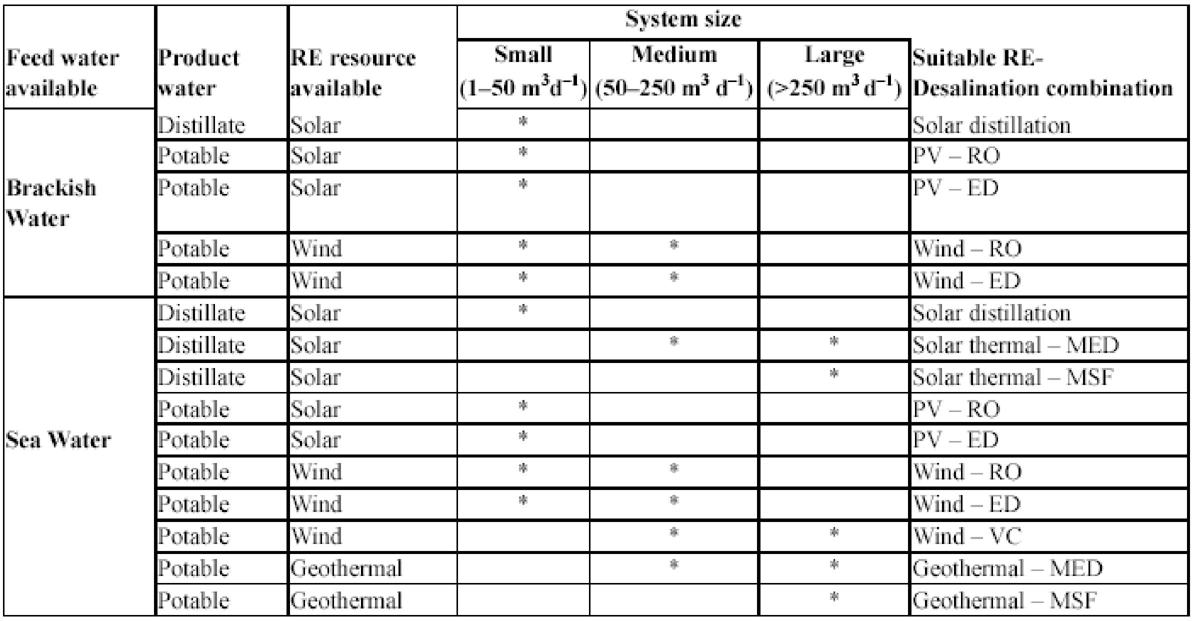
3. Analysis of prospective site with respect to resource availability

This third step allows the incorporation of data garnered from the environmental and meteorological appraisal of the site of interest.

Our first area of research should be to identify any renewable energy technology currently at use in our remote location. In today's technological climate one may find that an increasing amount of remote areas are effectively utilising the renewable sources at their disposal. If this is the case then it spares the analyst a great deal of time as an examination of this field has already been executed and the most attractive route highlighted. Such a situation allows analysis to instantly focus upon a more in-depth assessment of the technologies under consideration.

If however one finds that an area of interest is not utilising its renewable energy potential then it is essential to study and then deduce the most abundant renewable source at this location. Such an investigation can prove to be very important, as the results from this phase can be compared to those from step two and thus aids the process of highlighting the optimal RES solution.

A point worth noting here is that conventional evaluation systems ignore the possible opportunities that can be provided by remote regions. Above we have a process, which considers the possible implications of the site having an existing renewable energy program yet traditional methods seem to be ignorant of this fact, figure 4 is an example of this regular problem.



Feed water available	Product water	RE resource available	System size			Suitable RE-Desalination combination
			Small (1–50 m^{3}d^{-1})	Medium (50–250 m^3 d^{-1})	Large (>250 m^3 d^{-1})	
Brackish Water	Distillate	Solar	*			Solar distillation
	Potable	Solar	*			PV – RO
	Potable	Solar	*			PV – ED
	Potable	Wind	*	*		Wind – RO
	Potable	Wind	*	*		Wind – ED
Sea Water	Distillate	Solar	*			Solar distillation
	Distillate	Solar		*	*	Solar thermal – MED
	Distillate	Solar			*	Solar thermal – MSF
	Potable	Solar	*			PV – RO
	Potable	Solar	*			PV – ED
	Potable	Wind	*	*		Wind – RO
	Potable	Wind	*	*		Wind – ED
	Potable	Wind		*	*	Wind – VC
	Potable	Geothermal		*	*	Geothermal – MED
	Potable	Geothermal			*	Geothermal – MSF

Figure 4: Typical recommended renewable energy - desalination combinations [2]

From the above table we can see the proposal that small-scale MVC desalination should not be supported by wind energy, presumably as a result of the high costs associated with the installation of wind turbines (and indeed under normal circumstances this would be a fair assumption). However by taking into consideration the possible existence of a renewable energy framework within the local region, one would be able to make advantageous use of the existing structure. In this case we could utilise an existing wind turbine program to provide energy for a MVC desalination system.

One must be wary of the need for thorough research of the site of interest as it can reveal valuable information, negligence at this point may result in missed opportunities.

4. Economic Review

In theory it is possible that after the above stages we may be in a position where our analysis presents numerous RES that meet the requirements for utilisation. In such a situation we offer a final method of assessing which option offers the best answer (if after this step we are still in a position where multiple solutions present themselves then clearly they are both deserving of a comprehensive examination), by taking a tentative look at the economic aspects of each RES. At this early stage we still do not wish to immerse ourselves in too detailed a study, we therefore examine the common factors associated with each RES such as:-

- The typical total system costs for a stand-alone RES (in terms of £ per kilowatt-hour)
- The need for a energy storage medium
- Expected lifetime of major system components (i.e. PV modules, wind turbine structure etc.)
- Possible need for maintenance of other system components (i.e. energy converters etc.)

It is important to conduct a financial assessment of our possible RES options as the selection of a particular RE-desalination combination is going to be dependent upon both its success in meeting the necessary energy requirements and realising this achievement at a reasonable cost. As we shall see later trade offs are required between meeting our goals and do so at affordable prices.

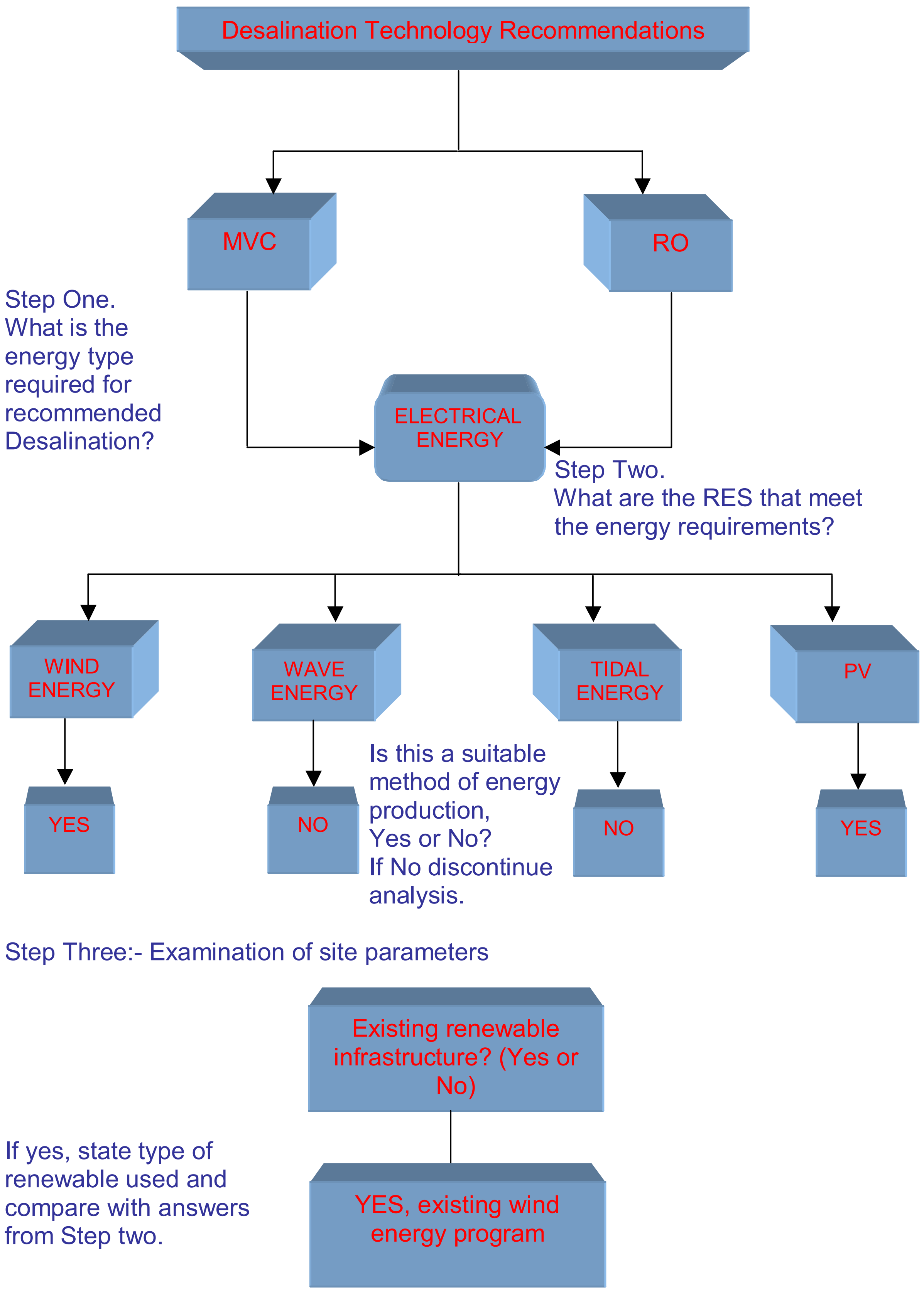
References

1. & 2. Oldach, R: “Matching renewable energy with desalination plants”, Middle East Desalination Research Centre, 2001, 22 – 25.

2.6 Lundy Island case study: Part two

Again we have implemented the previously discussed selection tool as part of the ongoing analysis of our case study. Figure 5 illustrates how this process was employed in the determination of assessing the RES potential of Lundy Island. One must remember that this chapter is all about selecting the routes that offer the best answers; it does not by any means actually evaluate how successful these ideas would be (this evaluation is left to the remaining chapters).

Of all the renewable selection tools available this one is unique in its flexibility and robustness. As we discussed in section 1.2 the selection method that we intend to use must have some level of interdependence between them. Here it is necessary to use the answers from the first selection method to help guide the second selection process. If we performed the RES analysis independently it could result in recommending an energy source, which is incompatible with the suggested desalination method. We would in all probability waste valuable time before realising this error. It is evident that by using a feedback process we are optimising the efficiency of the selection process.



Step One.
What is the energy type required for recommended Desalination?

Step Two.
What are the RES that meet the energy requirements?

Is this a suitable method of energy production,
Yes or No?
If No discontinue analysis.

Step Three:- Examination of site parameters

If yes, state type of renewable used and compare with answers from Step two.

Figure 5: Evaluation of RES potential on Lundy Island

A comparison between steps two and three yields that if renewably powered desalination process was to operate on the island it should be powered by wind energy. With regards to the RES assessment of Lundy we have been quite lucky in that an established wind energy program is in operation as common sense dictates that using PV’s in the UK for small-scale desalination will not be a fruitful partnership.

With regards to the technical assessment it was decided that work should focus on the design of an RO and an MVC plant both of which should be powered by wind energy.

Section Three

Systems Analysis

3.1 The Mechanical Vapour Compression system

The Mechanical Vapour Compression (MVC) system is the most attractive among various single stage desalination processes. The MVC system is typically defined as being compact, confined, and not requiring an external heat source (as opposed to other distillation systems). The system, as previously mentioned, is driven by electric power and is therefore suitable for sparsely populated areas [1]. Like in any other distillation process, the product water of the MVC system is almost pure water and the system has a low sensitivity to the feed salinity (this is unlike the RO system which as we shall see is very sensitive to this particular parameter) [2].

The MVC system does however have some disadvantages, maintenance and spare part requirements (for the compressor moving parts, which include blades, shaft sealing and motor) are quite high, limitations are imposed upon the vapour compression range (i.e. unit capacity), which include flow rate of compressed vapour and temperature increase of the compressed vapour. The first disadvantage increases the operating cost and dictates the use of highly skilled labour, we briefly touched upon this in our selection analysis but as we shall see it will now play a more prominent role, as this is an important factor when one is performing a feasibility study for remote regions. The second disadvantage limits the operation of the MVC system to low top evaporator temperatures, around sixty-seventy degrees Celsius (this however is becoming less of a problem) [3].

The basic principle of the vapour compression distillation process is shown below in Figure 6

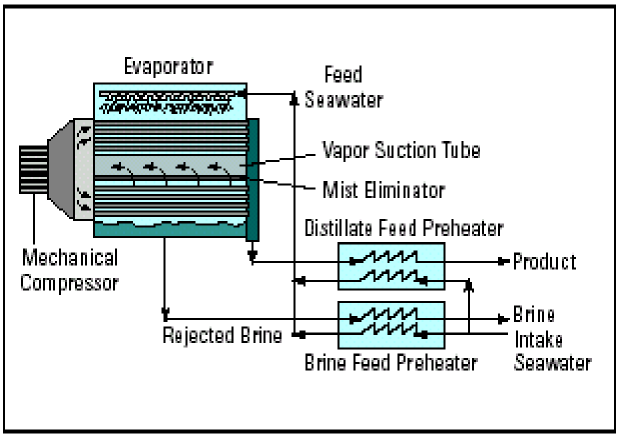


Figure 6: MVC system [4]

The feed seawater, after pre-treatment, flows in two parallel lines through plate heat exchangers. In these exchangers heat is transferred from the outgoing distillate and brine to the incoming seawater, thus meaning that the seawater temperature, T_c, will rise to T_f, the feed temperature.

The feed seawater, at temperature T_f, is then introduced into the combined evaporator-condenser unit (evaporator and condenser are a combined unit because they consist of a common bundle of tubes), where the feed is heated to its boiling temperature T_1 and then partially evaporated by the heating steam condensing on the other side of the heat transfer surface at saturation temperature T_2. This generated vapour is sucked by the compressor and discharged as superheated vapour at pressure P_2 (with saturation temperature T_2). The compressed vapour is introduced into the evaporator tubes; hence it condenses, after being cooled from temperature $T_{d'}$ (temperature at compressor exit) to saturation temperature T_2, and forms the product distillate D. The non-evaporated feed in the evaporator forms the blow down B. It is also possible to preheat the feed using an auxiliary heat supply, theoretically this shouldn't be necessary but as we shall see it is required for practical systems [5]. In such a system the main energy demand comes from the mechanical work to drive the compressor, therefore any accurate analysis of the compressor's energy requirements will be indicative of the whole systems energy consumption. If the plant is to remain in stable operation without a supplementary source of heat then it will require an extensive feed heat exchanger system (that could work out to be a substantial fraction of the total plant cost [6]).

The global advantage of a MVC system is the fact that it reuses heat rather than simply degrading it, the energy conservation within the MVC system is maintained by recovery of energy in the rejected brine and the condensate steam. Indeed the two heat plate exchangers can raise the feed temperature from a relatively low value (20 degrees Celsius) to a higher value within 3-6 degrees Celsius of the condensate and the rejected brine temperature. It is for this reason that it is preferred (when possible, remember the limitation imposed on unit capacity!) to other forms of distillation processes.

Advantages

- Little need for pre-treatment
- Reuse of systems heat energy means for lower levels of power consumption
- Compact.
- High quality distillate product

Disadvantages

- High maintenance requirements

- Scaling of heat transfer surfaces a problem
- Concentrate discharge potential harmful to local ecology
- Fairly expensive when compared to RO [7]

References

1. Voivontas, D et al: “*A tool for the design of desalination plants powered by renewable energies* “, Desalination 133 (2001), 175 – 198.

2. Plantikow, U: *“Wind-powered MVC seawater desalination — operational results”*, Desalination 122 (1999), Issues 2-3, 291 – 299.

3. Darwish, M: *“Thermal Analysis of vapour compression desalination system”*, Desalination, 69 (1988), 275 – 295.

4. & 7. www.cepmagazine.org/pdf/120232.pdf

5. Elsayed, M: “Rational basis for designing vapour compression water desalination systems”, Desalination, 58 (1986), 213 – 225.

6. Standiford, F: “Control in vapour compression evaporators”, Desalination, 59 (1986), 293 – 305

3.1.1 MVC system analysis: Defining important parameters

The system analysis of an MVC is quite a complex and lengthy one (even to someone with a relatively good understanding of the problems of heat transfer). Numerous journals have tackled the theoretical aspect of MVC [1.2] (indeed one will find the basic equations, which must form the backbone of any serious analysis in these texts) and collectively they instil a sense of confidence into any prospective analyst. However, generally these papers are misleading and are not representative of the practical problems that can occur if one blindly accepts the general assumptions that are made within these texts. Therefore an attempt has been made here to fully discuss the possible difficulties that can arise during the design process.

A quick glance of the MVC journal texts was sufficient to confirm that this is not a problem that can be solved on a sheet of A4 paper, the multitude of singular and interdependent variables clearly highlighted the need for a computer simulation of some kind. Due to its purely dedicated nature, in dealing with mathematical equations, the choice was made to use MATH CAD, it also allows us to isolate certain variables and observe the affects that they have upon the system as a whole.

The main aim of this analysis was to establish the energy consumption's of different components (such as the compressor) for various types of MVC systems in order to establish the best system suited to the Lundy Island project. In general the main operating parameters of any MVC system are the evaporator pressure and the compressor ratio (this is the ratio of P_c to P_e), therefore it was decided that the MVC analysis should focus on the effect that different evaporator temperatures and compression ratios have on the overall energy consumption of the system.

To give us results that where representative of a reasonable scope of analysis eight different evaporator temperatures (50 - 85 degrees Celsius) were modelled against three different compression ratios (1.3, 1.2, 1.1).

The decision was taken that the analysis of the system should not include the MVC pumping system (this consists of a seawater pump, dosing pump (for pre-treatment), and the brine and product pumps). It was considered that any alterations in the rate of pumping, due to increased rate of recovery (see section 3.1.2), would not dramatically affect the power consumption of the system. This would not have been the case had we been conducting a financial appraisal of the MVC designs. An examination of the factors affecting the Lundy Island case study suggested that the focus of the analysis should be placed upon the summertime scenario, as this clearly is the time of highest demand on Lundy, although a winter analysis would also be performed.

References

1. Darwish, M: *“Thermal Analysis of vapour compression desalination system”*, Desalination, 69 (1988), 275 – 295.

2. Elsayed, M: “Rational basis for designing vapour compression water desalination systems”, Desalination, 58 (1986), 213 – 225.

3.1.2 MVC system analysis: Thermodynamic Analysis

Before we discuss the problems presented by the MVC analysis it is essential that we state the assumptions [1] that were used to simplify the whole process.

- Isentropic compression by compressor.
- Negligible pressure drops in pipes and various heat transfer components.
- Specific heats of the feed F, distillate D, and the brine B are considered constant and equal to Cp1.
- Negligible boiling point elevation due to the salinity in the evaporator.
- The specific heat at constant pressure of the compressed vapour is considered constant and equal to Cp2.
- The latent heats of the evaporating vapour and condensed vapour are considered constant and equal to L.
- The plate exchangers have a maximum efficiency of 80% [2].
- The evaporator is completely insulated.

If one is familiar with the field of MVC desalination they will notice that one other usual assumption has been omitted - the brine, B, and distillate, D, leave the plate heat exchangers at the same temperature - the reason for which will be discussed in more depth later on.

It is not the aim of this thesis to discuss and explain in great detail every equation that makes up the whole analysis, but in order to illustrate the evolution of the MATH CAD (see Appendix 1 for the final complete version) program it is necessary to introduce some of the more important equations so the reader is familiar when we allude to them later on.

(1)
$$T_f := T_3 - \frac{\left[D\cdot C_{p2}\cdot\left(T_{4act} - T_5\right)\right]}{F\cdot C_{p1}}$$

When dealing with a system where so much reliance is placed upon the transference of heat energy, one must make sure that the latent heat of steam condensation gives enough energy to the evaporation side for evaporation. Clearly the value of latent heat of any given system is never going to change (provided the evaporator temperature and compression ratio stay the same), therefore the feed temperature must stay at a sufficiently high temperature so as to allow it to reach the necessary evaporation temperature. If the feed temperature is too low we have a scenario where to supply the required amount of energy means that the condensation side exit temperature will be very low such that it is lower than the saturation temperature of the evaporation side. In that case, heat transfer is not possible. Equation 1 [3] therefore calculates the temperature that the feed seawater must be at before entering the evaporator in order for successful operation of the MVC system.

(2)
$$\alpha := \frac{1}{\left[\left[1 + \left(\frac{F}{D} - 1\right)^{-1}\right]\cdot\left[1 + \left[\left(\frac{T_3 - T_1}{T_5 - T_3}\right) - \frac{D}{F}\right]^{-1}\right]\right]}$$

When the feed flow passes through the heat exchangers it should be distributed as (1-α)*F and $\alpha*$F in order to preheat the feed to T_f in both brine and distillate feed heaters. Naturally the need to calculate the respective flow rates of each heat exchanger is important as these values determine the effectiveness of the exchangers. Equation 2 [4] is used to establish the value of α,, which determines the flow rates through each heat exchanger.

(3) $$\alpha \cdot F \cdot C_{p1} \cdot (T_f - T_1) = B \cdot C_{p1} \cdot (T_3 - T_0) = A_b \cdot U_b \cdot \Delta T_{mb}$$

(4) $$(1 - \alpha) \cdot F \cdot C_{p1} \cdot (T_f - T_1) = D \cdot C_{p1} \cdot (T_5 - T_0) = A_d \cdot U_d \cdot \Delta T_{md}$$

Using Equations 3 and 4 [5] it is possible to calculate the heat exchange surface areas required for both the pre-heaters, this is important when one wishes to evaluate the capital cost of a particular MVC design. The equations are based upon the energy balance and heat transfer equations for each heat exchanger. From this data it is also possible to calculate the effectiveness of each heat exchanger, at the moment however we are only really interested in the first half of the equations that investigate the energy balance for each heat exchanger.

(5) $$T_0 := T_1 + (T_3 - T_f) + \frac{D}{F} \cdot (T_5 - T_3)$$

In most of the texts on MVC it is considered that the exit temperatures of the brine and the distillate are equal to one another, we can see that equations 3 and 4 are based on this assumption. Equation 5 [6] is used to determine this constant value (the initial MATHCAD program was developed using this equation, we shall discuss later why it was removed from the final version).

Also important is the determination of the rates of recovery for the MVC system. The recovery rate of any MVC system is based on numerous factors, such as seawater temperature, evaporator temperature and compression ratio, and as such all MVC design systems are based on assumed, not calculated, values. For this purpose it is obvious one must apply some common sense, and whilst recovery rates can reach above fifty per cent for many MVC plants [7,8] a far more restrained value of thirty-five was adopted. This is also a useful as it means that any evaluation of the system cannot be possibly termed as over optimistic.

The Evolution of the MATHCAD program

The initial MATHCAD program was filled with quite serious errors, what at first appear to be straightforward was proving both far more complex and time consuming. Matters where suspected to be gravely amiss when the two heat exchangers where required to operate at an effectiveness of 95% (in some cases these figures actually rose above 100%), and too have fairly large heat transfer surfaces (MVC operational history at similar temperatures demonstrated this to be incorrect [9]). It seemed that these results posed substantial questions as to the validity of certain equations.

A slight modification was made to the original model, which assumed that perhaps there was a slight variation between the feed temperatures coming from the two heat exchangers. The result of this was that whilst one of the heat exchangers seemed to stabilize, the other seemed to considerably worsen. After many alterations the source of the above problems was identified, it seemed that too much feed water was flowing through one heat exchanger thus leaving too little for the other. The reasons for this could be directly linked to equation 2 and therefore indirectly to the rate of recovery.

After a careful analysis it appeared that the aforementioned equations all potentially consisted of a common term, R (the rate of recovery), if this is the case it would be possible for one to determine a relationship between all five equations and subsequently calculate the value of R (designated as R_{theory} in the MATHCAD program), which would allow the operation of the system under the aforementioned conditions. It would also be possible to do this without actually stating exact values for T_f and T_o only the pre-selected values of the design process (e.g. evaporator temperature, distillate temperature, temperature at compressor exit and, the seawater temperature). After a lengthy process it became clear that it was possible to establish a polynomial equation in terms of R (this mathematical proof can be found in Appendix 2).

The result of this polynomial indicated that for the above system of equations to be true, R had to be prohibitively large (in the region of eighty percent and above). If one assumes that equations 1 and 2 must be true then it's not difficult to pinpoint the cause of the systems problems, such as :-

- The temperature, T_f, of the feed leaving the two heat exchangers is less than the value required for effective heat transfer in the evaporator, this indicated the need for an auxiliary heat source to add the necessary extra heat. A smaller value of T_f is also a consequence of the restrictions placed upon the process by the effectiveness of the plate heat exchangers.

- The exit temperature of the brine and distillate could not be equal to one another. This is due to the fact that, according to equation 5, T_o is dependent upon the rate of recovery, as the rate of recovery used in our system was evidently too low the values of T_o returned where too small. This in turn influences the values of effectiveness for the heat exchangers. As a result it was decided that a better method of calculating T_o would be to rearrange equations 3 and 4 and assume that these values are not automatically equal to one another. If we enter our original value for the recovery rate (35%) into these equations we find that they are not equal to one another, this further proves the case.

After this revelation, of sorts, real progress was made in the design of the program, although further alterations where required. It was found that the value of R_{theory} increased as the evaporator temperature also increased, it was therefore necessary to mimic a similar relationship in the MATHCAD program. This increase however has been pessimistically calculated (it is based on the relative increase in R_{theory} which is slowing down) and again no attempt was made to overstate the case for the MVC process (the proof is proven to be correct if one substitutes the value of R_{theory} into the MATHCAD program, this results in the above assumptions

The system was designed to be as flexible as possible, it allows the user to alter the main parameters to examine the effects upon the system, and it also allows the user to see the differences between the theoretical answers and the practical ones. Despite the fact that a total of 24 programs (48 if one considers the winter program as well) were used to analyse the system there still remains the potential for further investigation and improvement.

References

1, 3, 4, 5 & 6. Darwish, M: *"Thermal Analysis of vapour compression desalination system"*, Desalination, 69 (1988), 275 – 295.

7. Aly, H et al: *"Mechanical vapour compression desalination systems – a case study"*, Desalination, 158 (2003), 143 – 150.

8 & 9. Veza, J: *"Mechanical vapour compression desalination plants – a case study",* Desalination, 101 (1995), 1 – 10.

3.1.3 Analysis of MVC results

Of the compression ranges analysed it was decided that our analysis should focus on when rp=1.2. This was chosen for a number of reasons :-

1. At rp=1.3 despite having lower auxiliary heating levels, we have significantly high values for the compressor work (see Appendix 3), this is a direct consequence of the outlet pressure being quite large. Such values are generally unacceptable when considering cost-efficient small-scale desalination.
2. At rp=1.1 we will have very low values for the compressor work, however this benefit is offset by large surface areas required by both the evaporator-condenser unit, and the feed heat exchangers. The system also exhibits the need for a greater auxiliary heat input (see Appendix 5); this is a consequence of this particular set of designs having a higher required value of T_f . Despite the fact that such systems have been implemented on a larger scale the decision was taken not to consider this as an option for small-scale purposes.

As such the emphasis of the analysis was shifted to rp=1.2 which seemed to provide a middle ground between the need for low compressor work values and acceptable heat surface transfer areas.

As discussed in section 3.1.1 the summer analysis of the design would provide the real acid test as here the system and its constituent components are under the greatest strain, in terms of product water requirements. The winter results have been included in Appendices 6, 7, and 8 but they do not provide as much useful information as the summer study (as was initially expected), therefore this analysis will concentrate solely on the summer analysis (unless otherwise stated).

The first phase of results indicated the importance of an auxiliary heat supply. As a consequence of having to keep the effectiveness of the heat exchangers to within acceptable limits (< 85%) it was found that the resultant feed temperatures were too low for successful heat transfer within the evaporator. This points towards the need for an auxiliary heat source to raise the temperature to the required value of Tf (calculated in equation 1 on page forty-one. Figure 7 shows a comparison of the systems required Tf against the expected operational values.

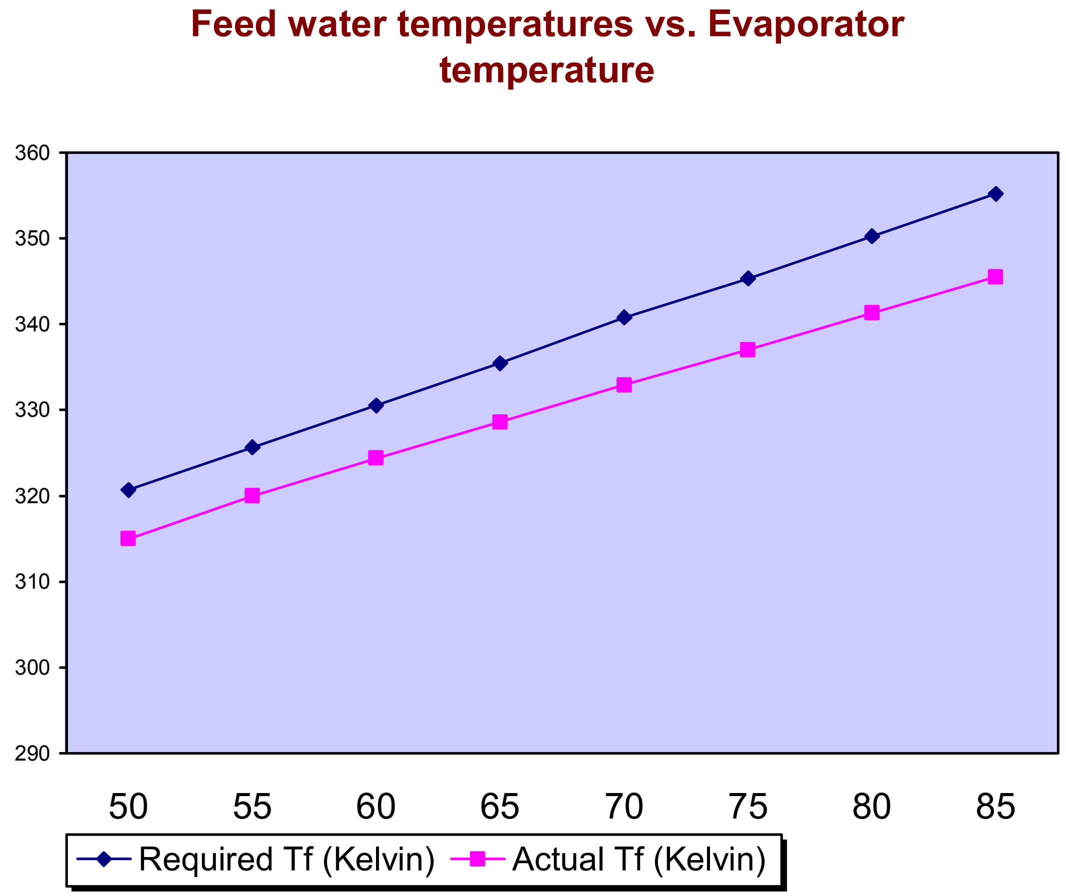


Figure 7: Feed water temperature vs. Evaporator temperature

As a result of the necessary restrictions placed upon the heat exchangers we find that the difference between the above parameters increases as the evaporator temperature also increases. This therefore indicates that the value of auxiliary heat, which is clearly essential for the systems operation, will also rise as the evaporator temperatures increase. By evaluating the figures returned from the MATHCAD program we can see this hypothesis is borne out (see Figure 8).

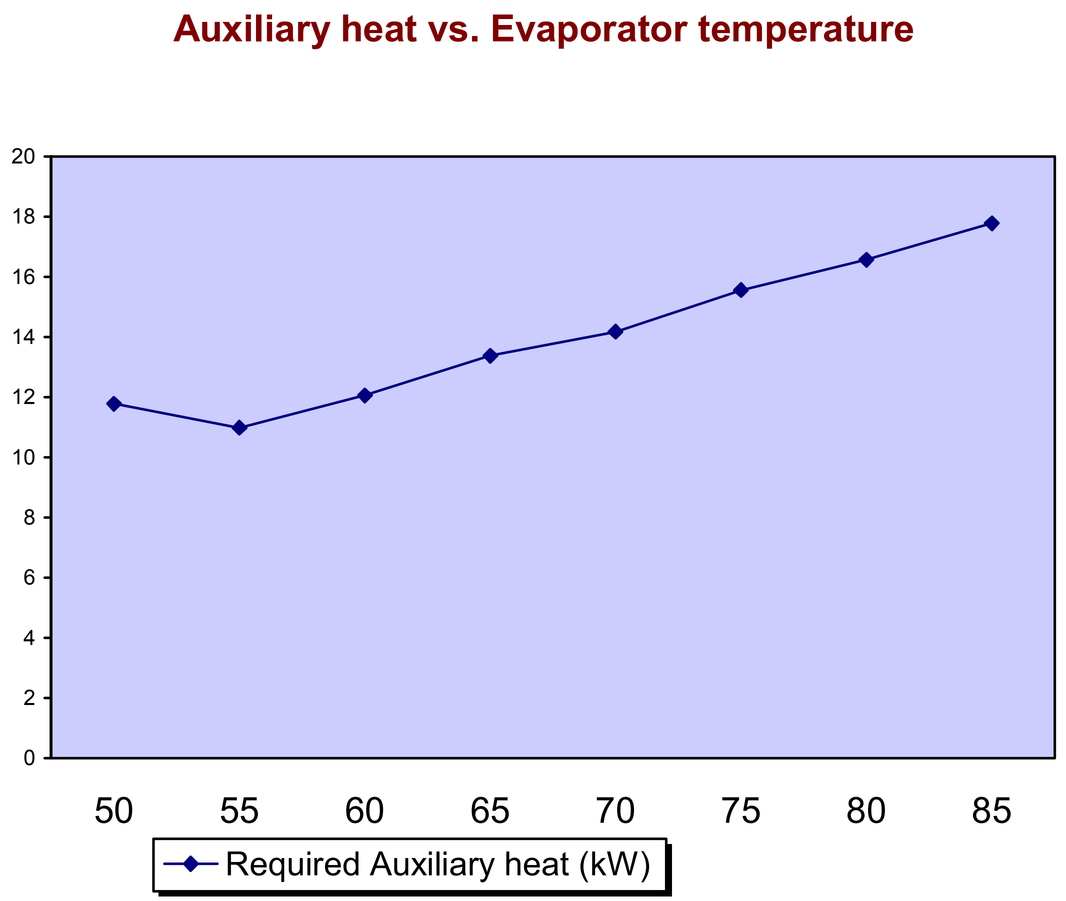


Figure 8: Auxiliary heat vs. Evaporator temperature

The above figure quite clearly illustrates the increased demand at higher evaporator temperatures. Despite the fact that these values are not large they imply a greater demand for electrical power to cover the auxiliary heat requirements, therefore when considering such a process one must also take this into consideration. Most practical

MVC systems [1, 2] make use of some type auxiliary heat source. Usually it will just be an electrical heater that will serve the purpose of raising the temperature to an acceptable level before entry to the evaporator.

As a consequence of the “inefficiencies” of the heat exchangers we find that it is not only the feed temperature is affected, by a process of inference (refer back to equations 3 & 4 on page forty-two) one may find that the exit temperatures of the brine and distillate are quite strongly affected. We have discussed in great detail, see section 3.1.2, the problems of conventional analysis when it comes to assessing values for these exit temperatures and our results indicate that this is very much a problem area.

Figure 9 illustrates the variation in exit temperatures with increasing evaporator temperature.

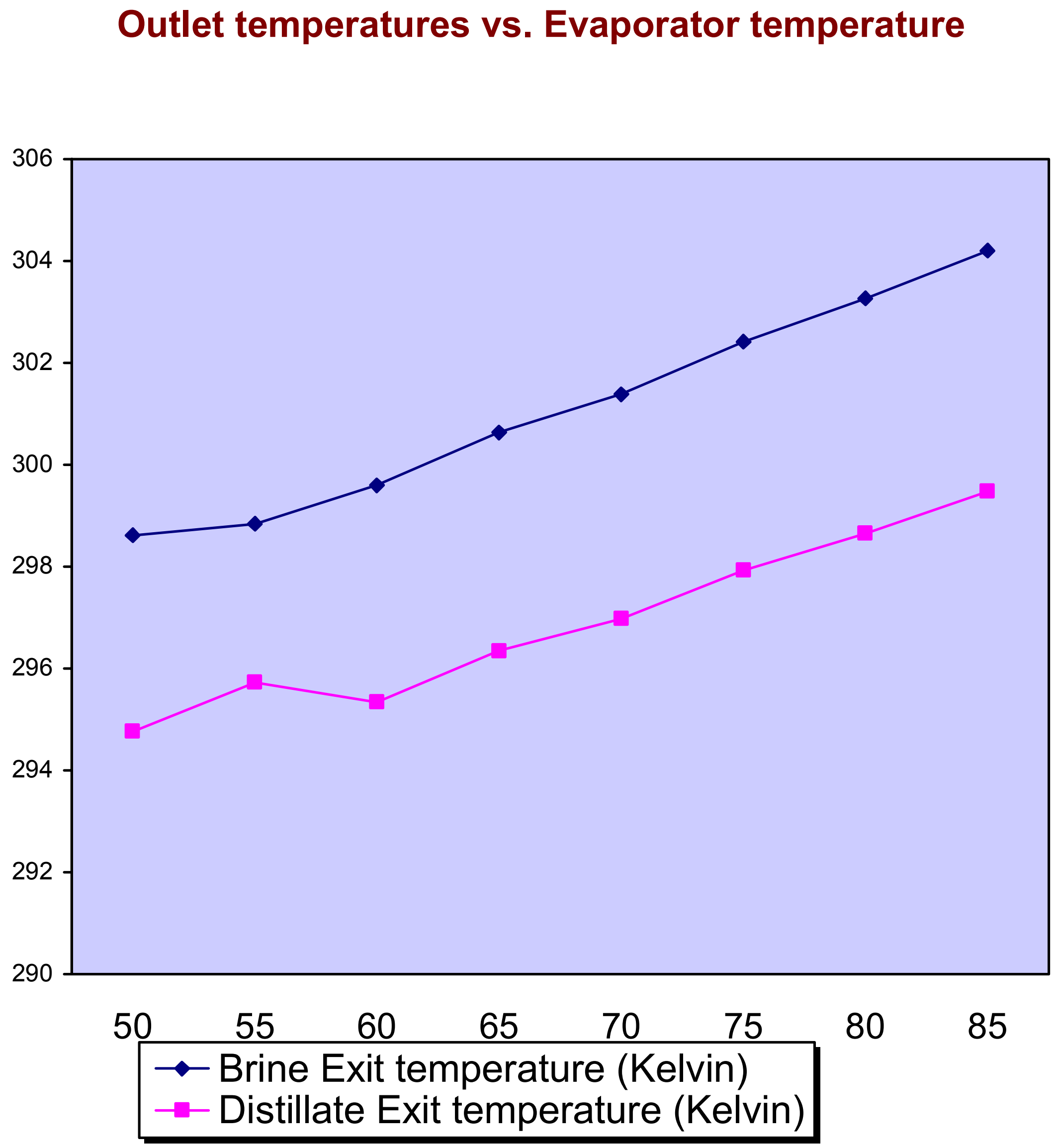


Figure 9: Outlet temperatures vs. Evaporator temperature

In most theoretical analysis of MVC systems the exit temperature can be found to be in the region of 293 K – 298K, and it would seem that the above figures generally fit this criteria. However most MVC studies have been performed in areas which have high seawater temperatures (>293 K) and as such they conform to one of the most important design criteria for any MVC plant, (that is the reject flows should only be in the range of 5 – 7 K greater than the original temperature of the original feed flow). As our exit temperatures are around 10 – 16 K greater than the seawater temperatures then clearly the exit temperatures for our system do not meet the aforementioned criterion. This is obviously a problem for the design of the plant and it seems the only way to overcome this problem is to somehow post-treat this reject water before expelling into back to the sea. The possibility does remain however, for us to again pass this reject stream through the seawater stream (before the main heat exchange system) but this adds to the complexity of the plant and thus serves to hamper what is meant to be an advantage of the MVC plant.

The work performed by the compressor is very reasonable for such an energy intensive process; because of the low compression ratio less work is required to compress the steam to the required exit pressure. As the equation used in the MATHCAD program states, the operation of the compressor is independent of temperature, and as such it is the inlet pressure, compression ratio, and the specific volume of the steam that determine the amount of work.

Recently a lot of emphasis has been put on low-temperature desalination systems [3, 4] (usually this means the evaporator temperature will be in the region of 323 – 338 K), as the inlet pressure of these systems is very low one can hope to achieve excellent system performance, however to a large degree these benefits are offset by the occurrence of large specific volumes at these low pressures. Nonetheless In our analysis it was found that lower evaporator temperatures did indeed offer reduced levels of compressor work, as indicated in Figure 10.

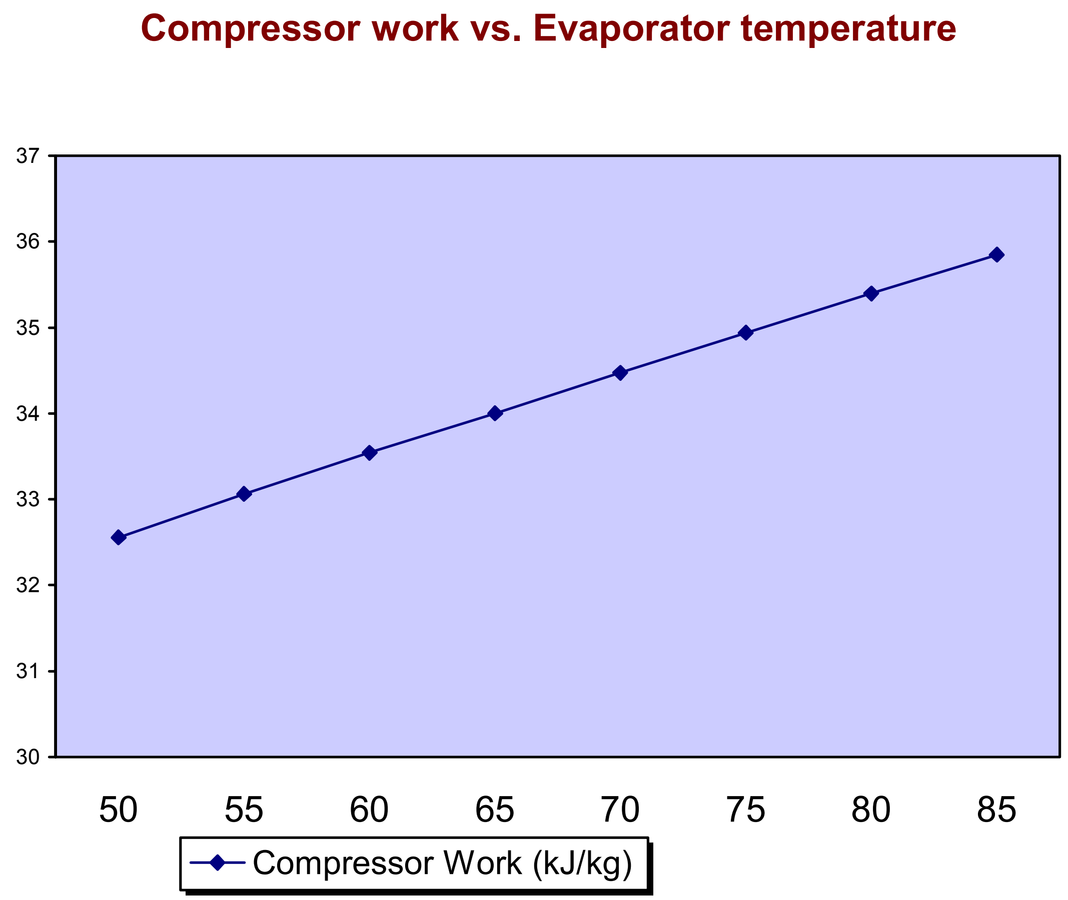


Figure 10: Compressor Work vs. Evaporator temperature

Figure 10 indicates a linear relationship between the levels of compressor work and the levels of evaporator temperature. If we can make the general assumption that the compressor is the main energy requirement of an MVC system (such an assumption is justified if one considers that the pumping system used in all these MVC designs will be constant, as they are more or less pumping similar feed levels, and that the only varying energy consumption level is that of the compressor) than the levels of power consumption will also be indicative of this relationship. When evaluating the power consumption we analyse in terms of kilowatt-hours used per unit product of distillate. This is a process common to evaluating all desalination techniques, and helps to establish a standard method of system comparison.

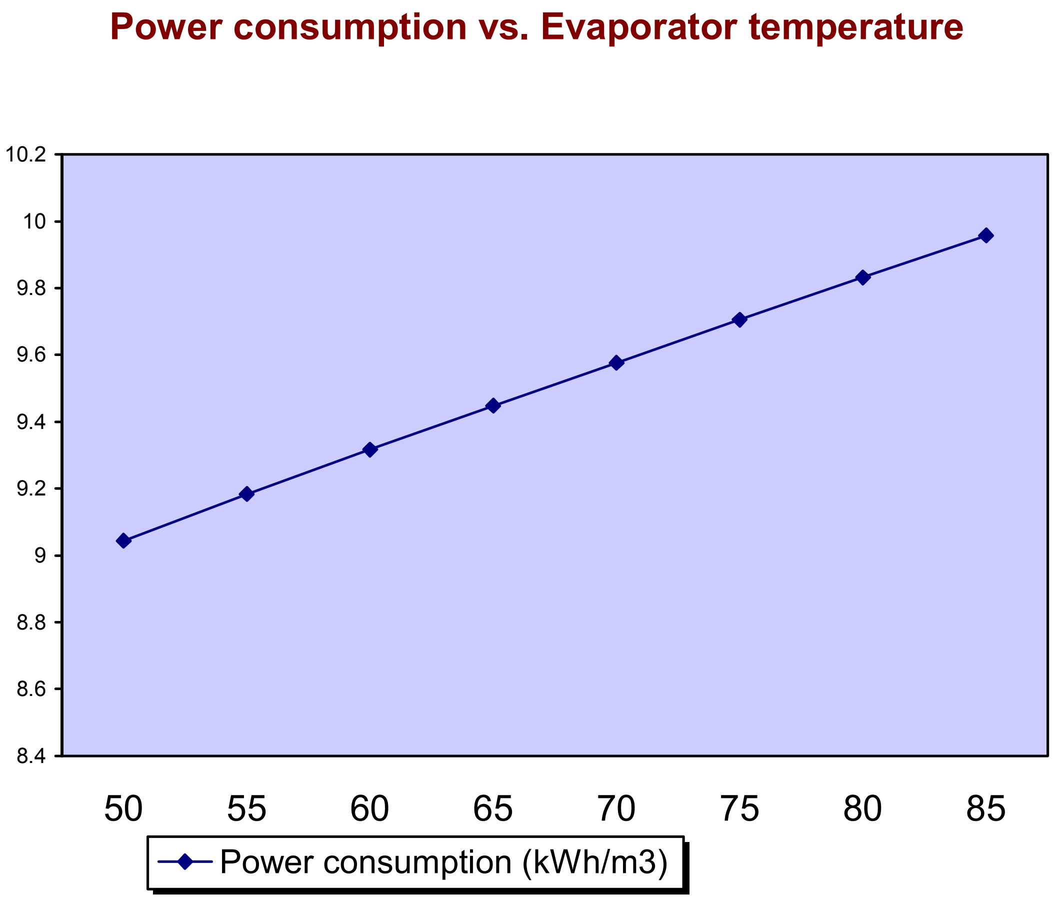


Figure 11: Power consumption vs. Evaporator temperature

Figure 11 again confirms our above hypothesis. It is possibly Figures 10 & 11 that will have the greatest impact upon the entire decision making process

References

1. Veza, J: *“Mechanical vapour compression desalination plants – a case study”,* Desalination, 101 (1995), 1 – 10.

2. Aly, H et al: “Mechanical vapour compression desalination systems – a case study”, Desalination, 158 (2003), 143 – 150.

3.1.4 Conclusion of MVC analysis

Once the actual process of establishing a useable MATHCAD program was overcome the interpolation of the design results was very straightforward. The above results all suggest that a low temperature desalination system is more favorable than more conventional system designs. Keeping power consumption to a minimum requires not only that the evaporator heating surface to be larger so it can operate at lower temperature differences, but also that the feed heater surface be larger to keep the system in balance. It is clear from this that we cannot offer a perfect system and we must be prepared to accept certain trade-offs during the design process.

The main benefit of high temperature desalination techniques is that they offer slightly higher levels of water recovery and smaller evaporator surface areas, however they require greater levels of auxiliary heat and consume larger levels of power. It would seem that the advantages of low-temperature distillation seem to far outweigh what the above can offer us and gives the impression of a better-rounded system. Low temperature distillation is typically characterised by :-

- Rate of scaling on heat transfer surfaces is less at smaller evaporator temperatures

- Lower rates of power consumption (this is typical of many low temperature distillation processes [1,2]

- Lower auxiliary heating requirements

- Low exit temperatures for brine and distillate.

The inherent difficulties (maintenance etc.) obviously still remain but this is a system characteristic and would be present in any MVC system.

Based on the above information, along with detailed research on the operational history of MVC plants it seems quite clear than low temperature distillation is the way forward. Of the systems discussed here it has been concluded that an evaporator temperature of sixty degrees Celsius would allow optimum performance purely because there is a greater operational experience at this temperature [4,5].

References

1. Veza, J: *“Mechanical vapour compression desalination plants – a case study”,* Desalination, 101 (1995), 1 – 10.

2. Aly, H et al: “Mechanical vapour compression desalination systems – a case study”, Desalination, 158 (2003), 143 – 150.

3.2 The Reverse Osmosis system

Put quite simply Reverse Osmosis (RO) is a membrane separation process, it was developed in direct competition with conventional distillation processes, such as MVC, and over the past two decades this process of seawater desalination has gained much popularity [1]. At first RO was deemed suitable only for small – medium scale operations, however it is now common to larger scale desalination applications utilising this method. As a result of its typically modest energy consumption and ever increasing flexibility of operation, RO is taking over from conventional distillation methods and currently accounts for 50% of all desalination processes [2].

It is easy to describe the mechanics of RO if one looks at the well-known natural phenomenon of osmosis. Here when a salt solution is separated from pure water by a semi-permeable membrane, water tends to diffuse through the membrane into the salt solution. The RO process that causes water in a salt solution to move through a semi-permeable membrane to the permeate water side can be accomplished by applying in excess of the natural osmotic pressure of the salt solution [3].

In the basic RO system (see Figure 12 below) the feed water is pumped into a closed container against the membrane, to pressurise it.

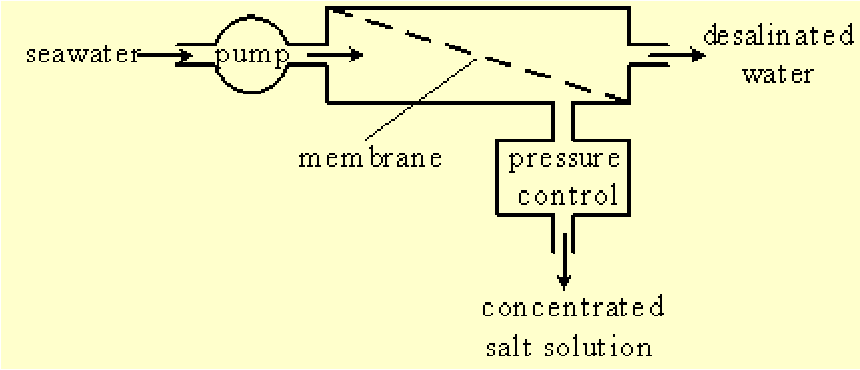


Figure 12: How RO works [4]

As the product water passes through the membrane, the remaining feed water and brine solution becomes more and more concentrated. To reduce the concentration of dissolved salts remaining, a portion of this concentrated feed water- brine solution is withdrawn from the container. Without this discharge, the concentration of dissolved salts in the feed water would continue to increase, requiring ever increasing energy inputs to overcome the naturally increasing osmotic pressure.

No heating or phase change takes place; the major energy requirement is for the initial pressurisation of the feed water, usually by a high-pressure pump. For brackish water desalination the operating pressures range from 17 –28 bar, and for seawater desalination from 55 – 70 bar [5],

A typical RO system consists of four major components/processes [6]:-

Pre-treatment

The incoming feed water is pre-treated to be compatible with the sensitive membrane modules, in RO this can make for a fairly extensive process. The extent of pre-treatment depends on the type of feed water; seawater requires the greatest degree of cleansing. In a seawater pre-treatment process we have a chlorination system, which is basically a dosing pump that administers a sodium hypochlorite solution in order to kill organisms. The next stage is a set of multi-media filters; the first filter is for sands and the other for activated carbon. The last phase is a cartridge filter, which ensures that particles larger than 5 micron, carried over from the dual media filters, will not enter the membranes. However, despite such rigorous preventative measures membranes still require periodic cleaning.

Pressurisation

A high pressure pump (HPP) raises the pressure of the pre-treated feed water to an operating pressure which is appropriate for the membrane, and (as mentioned above) creates a suitable pressure differential above the osmotic pressure of the salt water thus allowing for permeate production.

Separation

The permeable membranes inhibit the passage of dissolved salts while permitting the desalinated product water (permeate) to pass through. Applying feed water to the membrane assembly results in a freshwater product stream and a concentrated brine reject stream. Because no membrane is perfect in its rejection of dissolved salts, a small percentage of salt passes through the membrane and remains in the product water. However recent advances in membrane technology have produced membranes that can reject as much as 99% of salts present in the feed. In the case of seawater it would mean a reduction of 35000ppm (parts per million) to only 350ppm, which is an acceptable level for drinking.

Stabilization

The product water from the membrane assembly usually requires pH adjustment before being transferred to the distribution system for use as drinking water. In this case the pH value is usually altered to around 7.5 – 8.5.

The major operational elements associated with the use of RO technology will be the day to day monitoring of the system and a systematic program of preventative maintenance. Preventative maintenance includes instrument calibration, pump adjustment, chemical feed inspection and adjustment, leak detection and repair, and structural repair of the system on a planned schedule. The main operational concern related to the use of RO units is fouling. Fouling is caused when membrane pores are clogged by salts or obstructed by suspended particulates. Membrane fouling can be corrected by backwashing or cleaning (about every four months), and by replacement of the cartridge filters (about every eight weeks). It is essential that any RO plant is maintained, operated and monitored by trained engineering staff, however a small-scale RO plant could be managed by a single person.

Advantages

- Typically low installation costs, lower than those of distillation technologies.
- Modular design allows for simple expansion and increase of the production capacity.
- Efficient membranes lower post-treatment requirements.
- Low specific power consumption.

Disadvantages

- Membranes are sensitive to abuse
- An extensive spare parts inventory must be maintained
- Has a higher cost when compared to rainwater harvesting (the usual approach on Lundy Island)
- There may be interruptions of service during stormy weather for plants that use seawater (a possible problem for use on Lundy)

References

1. Malek, A et al: “Design and economics of RO seawater desalination”, Desalination, 105 (1996), 245 – 261.

2. Al-Enezi, G et al: “Design consideration of RO units: case studies”, Desalination, 153 (2002), 281 – 286.

3. Liu, C et al: “Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control”, Desalination, 150 (2002), 277 – 287.

4. urila.tripod.com/Seawater.htm

5 & 6. www.oas.org/publications/Unit/oea59e/ch20.htm

3.2.1 Energy recovery in RO

In the last section we discussed the advantages of RO, however we did not discuss an additional advantage that RO offers – the possibility of recovering energy from the processes reject brine stream.

Today there are various energy recovery (ER) devices in use, such as the Pelton wheel turbine, the turbo charger, and the pressure exchanger. In the following analysis, and throughout the remainder of this investigation, we shall be concentrating on the most popular method of ER – the pressure exchanger.

The pressure exchanger system (PES) utilises the principle of positive displacement to transfer the energy in the reject stream directly to the membrane feed stream. The integration of the PES for use an ER system in a desalination plant is shown in Figure 13.

As in conventional RO plants, the seawater is drawn in by a feed pump and transported to the pre-treatment section. After passing pre-treatment the feed flow is parted into two flows of different sizes, depending on the rate of conversion in the RO unit. The smaller flow is led to the high pressure pump and the larger on with the same volume as the brine flow leaving the RO modules is pressurised by the pressure exchanger [1].

In the PES the high pressure of the brine leaving the RO modules is directly transmitted to the feed. Due to pressure losses in the RO modules, the connecting pipework and in the PES itself, a pressure rising pump is necessary to compensate these losses.

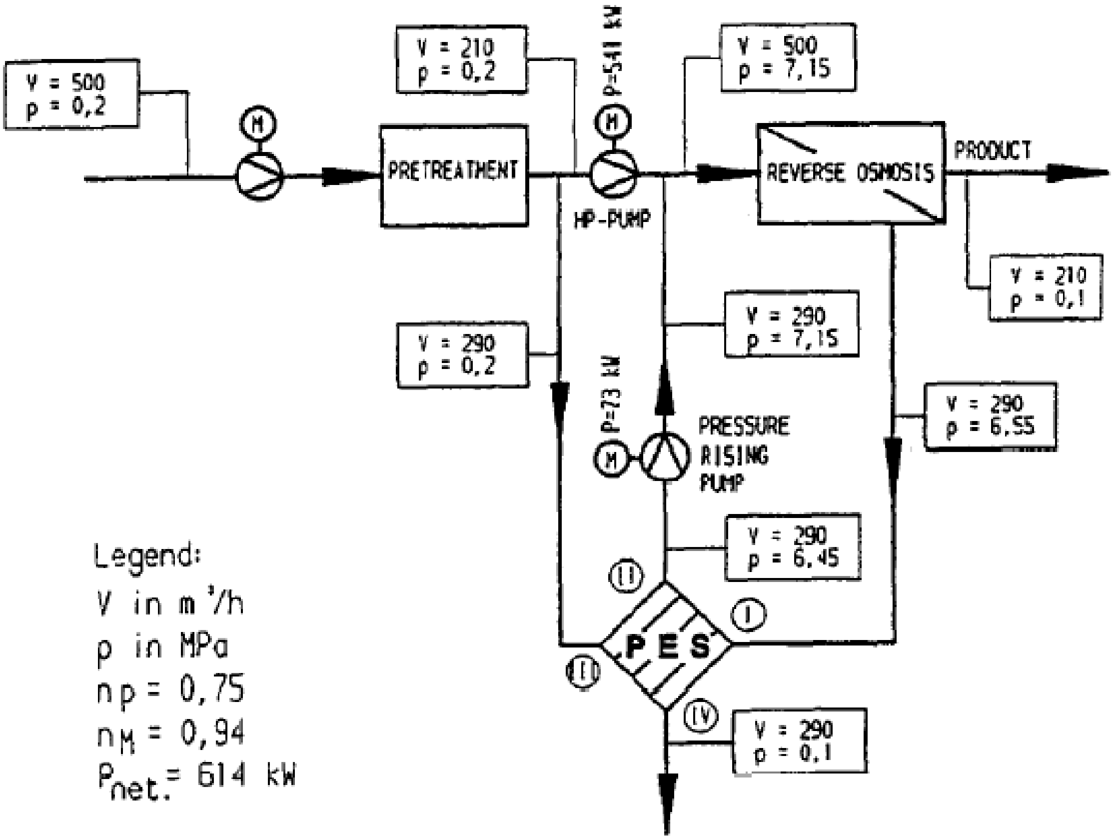


Figure 13: The integration of an energy recovery device into RO [2]

The principle of the pressure exchanger can be illustrated with the help of a one-chamber scheme, shown in Figure 14.

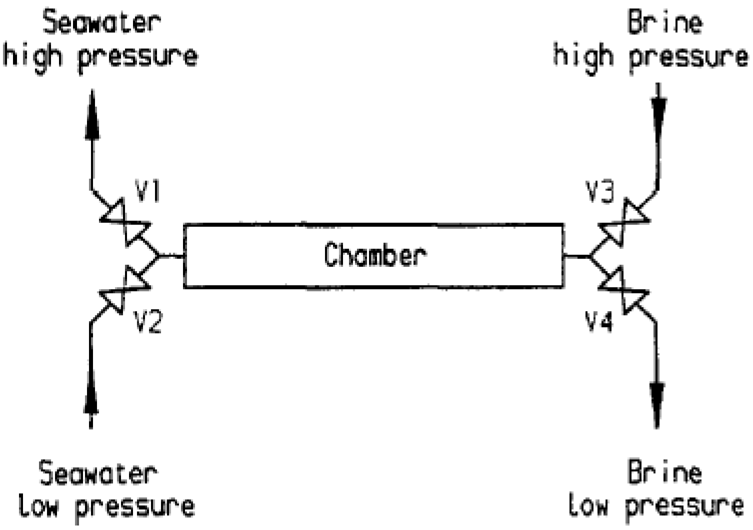


Figure 14: Single Chamber scheme [3]

At first the chamber is filled with low-pressure seawater – the valves V1 to V4 are closed. Then the chamber is pressurised by opening a bypass valve and after this valves V1 and V3 are opened. Now the incoming high-pressure brine pulls the seawater to the pressure rising pump and further to the RO system. When the chamber is filled with brine, valves V1 and V3 are closed and the chamber is depressurized. Valves V2 and V4 are opened, and incoming low-pressure seawater pulls out the brine. Then a new working operation cycle begins.

One chamber would operate discontinuously, but the configuration of three chambers (see Figure 15) has nearly a constant output.

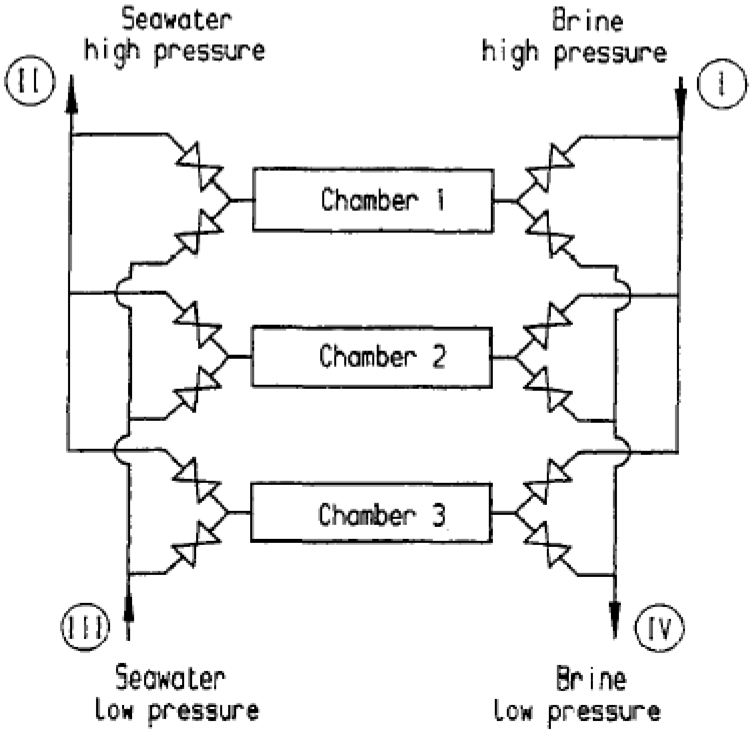


Figure 15: Schematic of PES [4]

The ER from the brine depends on the amount of brine and on its pressure, which in turn depends primarily on the salinity of the feed. This is perhaps why ER has often been referred to as being more adaptable to seawater rather than brackish water desalination.

It was generally thought that ER should only be used in plants of a fairly large nature (>100m^3 /day) however attempts have been made to integrate ER into much smaller scale plants [5]. We shall analyse the PES system both in terms of its productivity and also its cost.

References

1, 2, 3 & 4. Geisler, P et al: "Pressure exchange system for energy recovery in reverse osmosis plants", Desalination 122 (1999), 151 – 156.

5. www.dti.gov.uk/energy/renewables/publications/pdfs/sp200305.pdf

3.2.2 RO system analysis: Defining important parameters

Using the same method as for MVC we evaluated RO by using the most important system factors – the membranes and the ER system.

When considering how to investigate the membranes it became obvious that the possibilities offered by a multiple membrane array should be considered. Most practical systems make use of this by connecting modules in groups of six or seven.

The operation of such a system is illustrated in Figure 16.

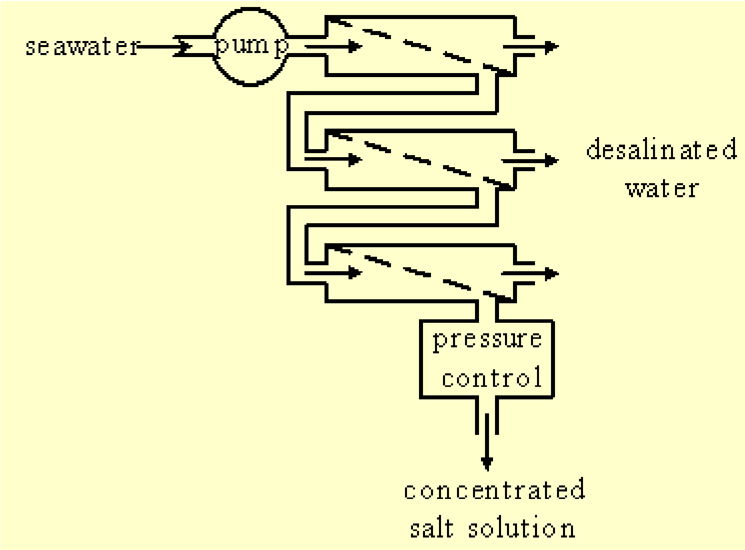


Figure 16: Series configuration of membranes [1]

Seawater flows into a first module where a certain amount of it (dependent on the membrane type) penetrates through the membrane to become permeate water. The rest more concentrated water flows to a second module where again part of it penetrates through the membrane and part of it continues to the next membrane.

The salt concentration and therefore also the osmotic pressure increase at each consecutive module, while the overall pump pressure is nearly the same in all of them. The flow rate through the membrane is proportional to the difference between the pump pressure and the osmotic pressure (equation 2). Therefore, the pressure difference and the flow rate through the membrane are highest at the first module. They decrease at each consecutive module, and are lowest at the last module.

In this system there is no need of overpressure to drive water through the membranes if sufficient number of modules are connected in series. As we are dealing with a small-scale design we must take care not to add too many membranes, as clearly the cost will be too high. In our analysis we have decided upon a maximum (series) configuration of four membranes.

The ER analysis is fairly straightforward; care is all that is required when calculating the new flow rates.

References

1. Urila.tripod.com/Seawater.htm

3.2.3 Analysis of RO results

As a consequence of the decision to include ER into our analysis it was found that the original MATHCAD program had to undergo a major revision. The inclusion of an ER device meant that we now had to perform both a technical and an economic evaluation of the RO system, in order to establish the energy savings afforded by the ER process and the price at which they shall come.

The main requirement of the MATHCAD (given in Appendix 9) program was to establish the power consumption of the entire process, in order to do this it was necessary to evaluate the properties of the membrane module that we expected to use in this process. In particular the analysis of the membrane centred on determining its flow rate factor, Kf. This is an important variable as it dictates the flow of permeate through the membrane per bar of the applied pressure differential. In order to calculate Kf we must model our computations upon the membrane module that we intend to implement in our RO system. For this purpose the membrane analysis was based upon the “FILMTEC SW30HR-320 High Rejection Seawater RO Element”. It is from this membranes data sheet that we can find both, the recovery rate and the information necessary to calculating Kf.

As mentioned above, the reworking of the MATHCAD program to incorporate the ER device was a fairly significant process but its inclusion seemed, and still does, vital to establishing the usefulness of the RO design. A quick perusal of the MATHCAD program indicates that the pumping system is the main offender in terms of energy consumption. It therefore makes perfect sense to examine the potential of an ER device, which potentially allows for lower levels of consumption.

However the membrane manufacturers data sheet [1] was not only useful in determining membrane conditions, it also helped in quantifying other system parameters (such as the high pressure pump requirements) and thus the design of the RO system is such that we can expect optimal performance from the membranes.

The MATHCAD program as a whole presented no particular difficulties, and was more of a lengthy process (when one considers that we must assess both summer and winter conditions) rather than a complex one. The results returned by the system seemed, in a general sense, to support our expectations, however some sections of the results proved rather more interesting than anticipated. Unlike the study of the MVC system, to complete the RO analysis it was necessary to perform a basic economic assessment of the eight different designs. Such a recourse was deemed necessary because of the need to have some method of effectively assessing each design (in the case of MVC we usually do not have much variation in cost when analysing figures over a constant compression ratio, however for RO the addition of extra components indicates the need to quantify the expected increase in cost and measure this against the perceived operational benefits).

The analysis of results has been divided into a discussion on the system without ER, the system with ER and then a comparison of these results (as before all results refer to the summertime scenario unless otherwise stated). In general the results demonstrated that with the addition of both extra membranes and an ER device we will witness increased system efficiency (in terms of both improved recovery values and lower levels of power consumption). However an individual breakdown of the results for certain system parameters indicate that matters are not as easy as they seem (an entire catalogue of results acquired from the RO study can be found in Appendix 10).

Without Energy Recovery

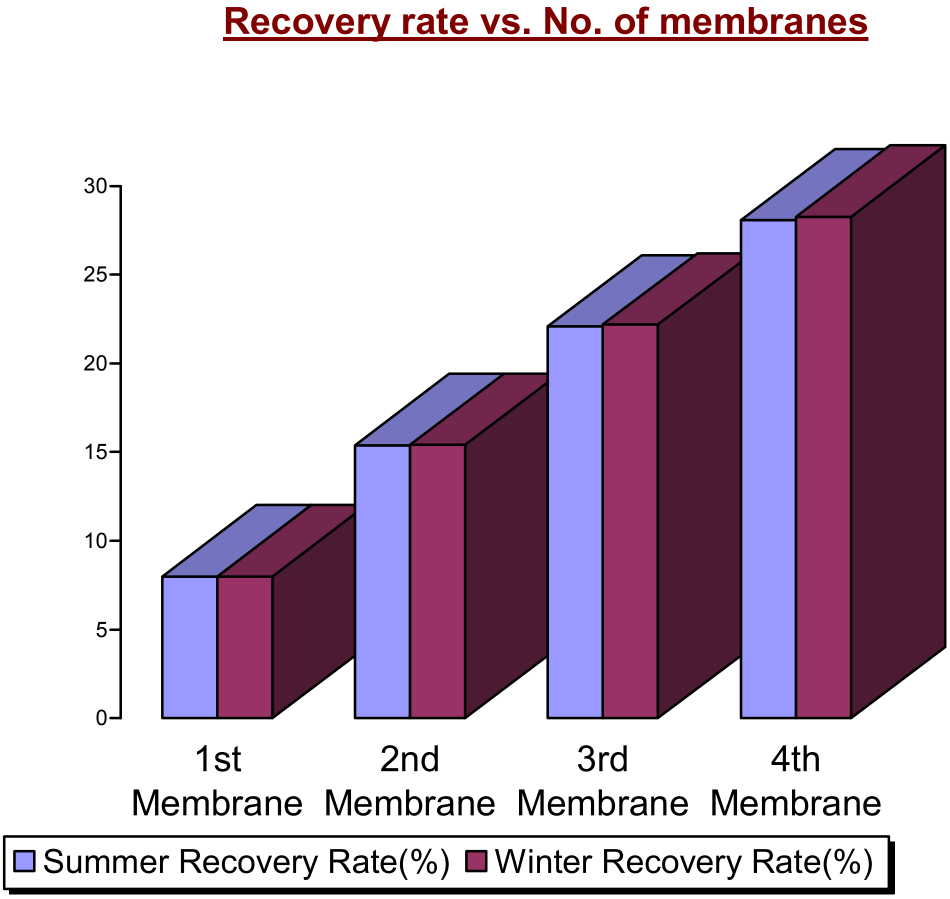


Figure 17: Recovery rate vs. number of membranes

Figure 17 illustrates the rate of increase in the recovery rate, which occurs with the addition of a new membrane to the series array. One can just make out that the recovery rate per membrane increases at a faster rate during winter. This is purely because the osmotic pressure of the seawater during this period is smaller than the expected summer value of osmotic pressure. This increase in the rate of recovery means a decrease in power consumption of the RO system (see figure 18 below). This is a consequence of the seawater pump (and the high pressure pump) having to pump lower amounts of feed water in order to deliver the required amount of permeate flow.

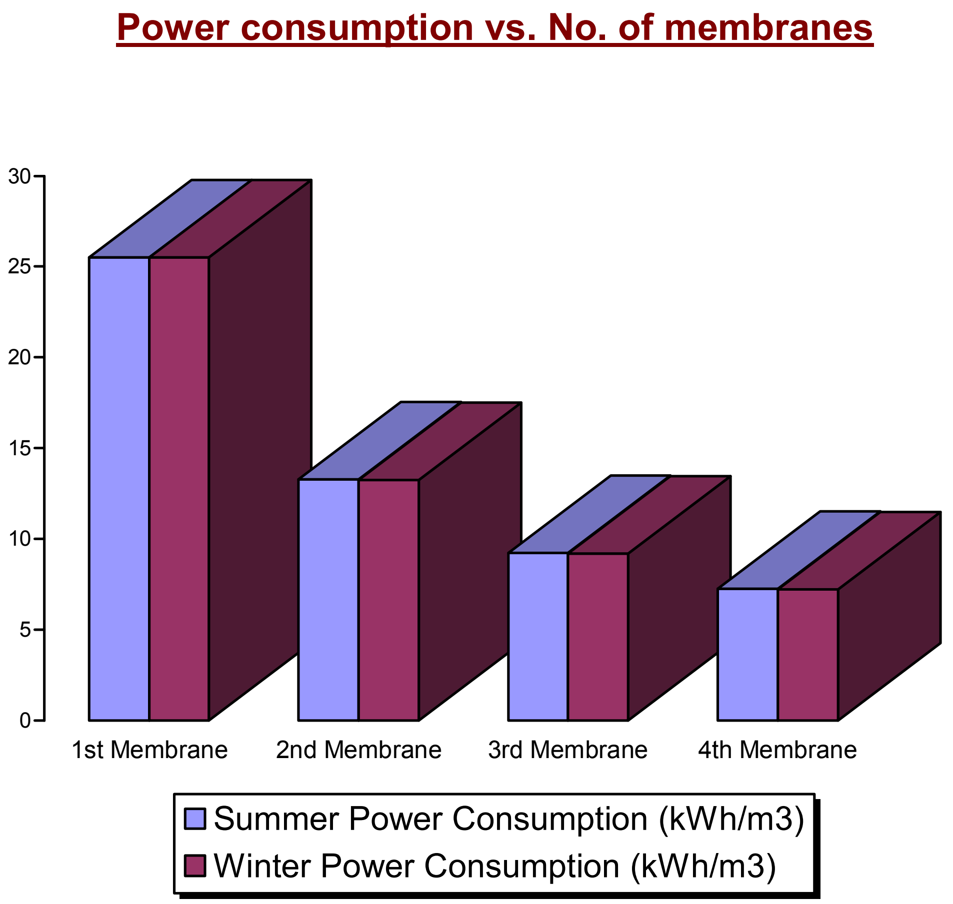

Power consumption vs. No. of membranes

Figure 18: Power consumption vs. number of membranes

As shown below in Figure 19, we see that the increase in productivity afforded by each new membrane is getting considerably smaller. This is again mainly due to the fact that increasing levels of osmotic pressure mean that the membranes become less efficient in the recovery of permeate water. In the RO summer design we can expect recoveries of :-

- 8% recovery from the first membrane

- 7.53816% recovery from the second membrane
- 6.7073% recovery from the third membrane
- 5.9837% recovery from the fourth membrane

This lower recovery rate means that a double membrane system will have to pump more feed water than one would expect hence the decreasing rates of process productivity. In such circumstances one must compare the financial aspects of certain variables and determine whether these costs are suitable for the required system. We must remember that we are dealing with an analysis of a small-scale desalination process so we must carefully consider the possible economic impacts, we will however deal with this later.

Number of Membranes	Power Consumption (kWh/m3)	Power Reduction	Increase in system efficiency (%)
1	25.19066	0	0
2	13.272523	11.918137	47.5
3	9.242331	4.030192	30.37
4	7.272307	1.970024	27.1

Figure 19: Levels of system performance

With Energy Recovery

The ER system has no actual affect upon the recovery levels of the RO design but as one would expect the system with ER allows the system to achieve even lower levels of power consumption, as indicated in Figure 20. What we unexpectedly find though is that the ER system offers smaller improvements as the number of membranes increases. This could be a indirect consequence of the increasing osmotic pressure what we mean by this is that as the recovery rates eventually level we will also witness a levelling off of the brine flow. With each additional membrane the level of brine will alter less and less meaning that there is less room for improvement.

If we make a comparison between the two levels of power consumption we can see the savings that an ER device will afford us (shown in Figure 21). When evaluating ER we must remember to factor in the power consumed by the pressure booster pump, which compensates for the losses within the system. It is also necessary to re-evaluate the pumping system, as with the addition of an ER system it will have different (smaller) flow rates. The MATHCAD program takes all of these parameters into account.

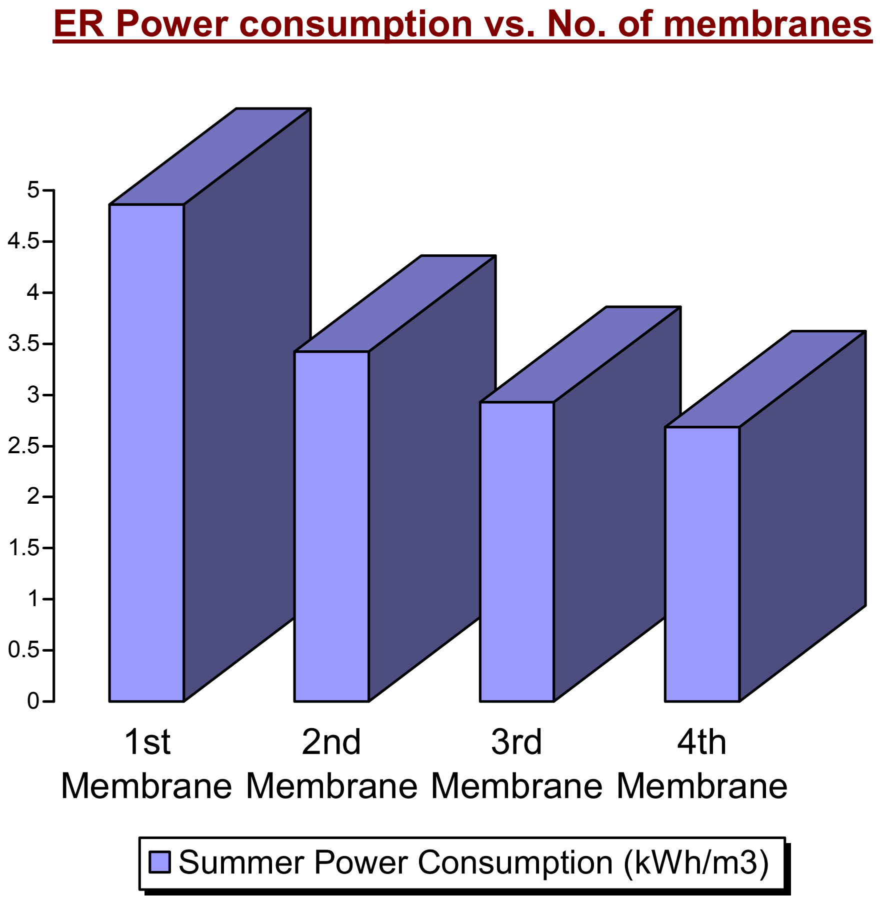


Figure 20: Power consumption of system with ER

If we make a comparison between the two levels of power consumption we can see the savings that are afforded by an ER device (shown in Figure 21). When evaluating ER we must remember to consider the power consumed by the pressure booster pump, which compensates for the losses within the system. It is also necessary to re-evaluate the pumping system, as with the addition of an ER system it will have different (smaller) flow rates. The MATHCAD program takes all of these parameters into account.

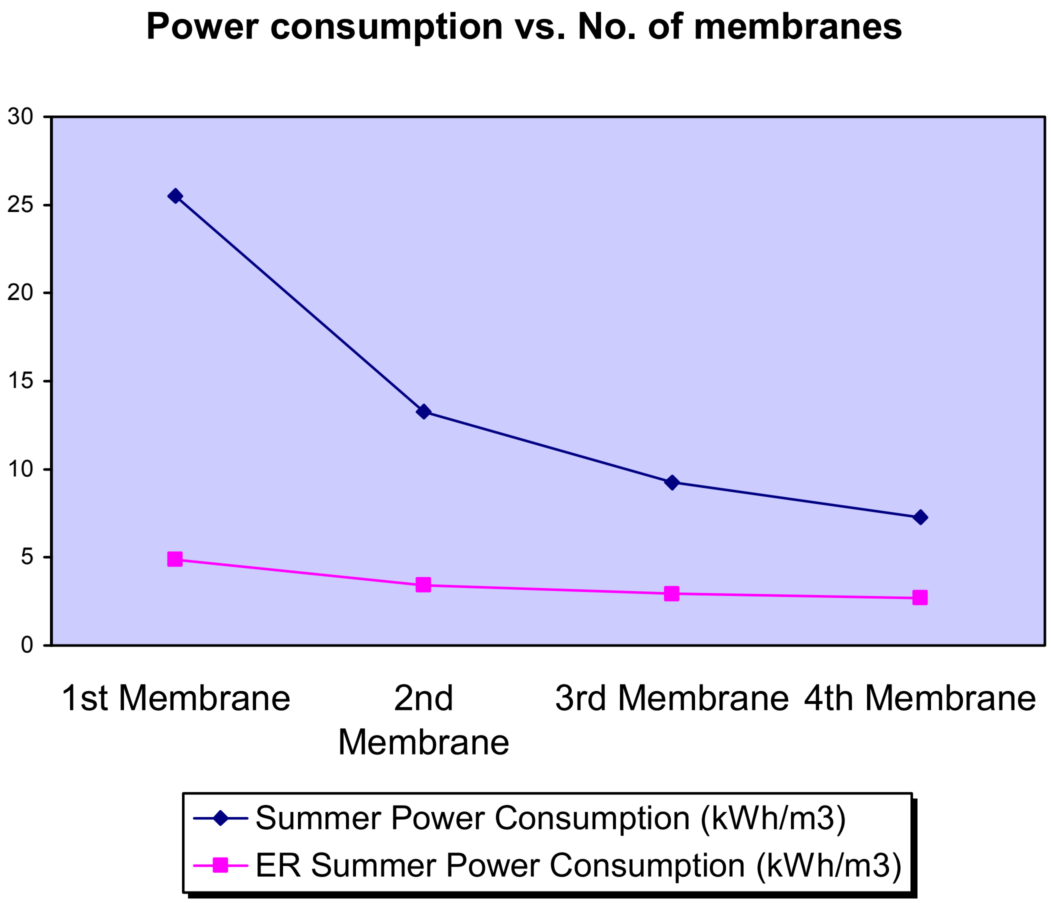


Figure 21: Comparison of power consumption levels

Figure 21 highlights what we have been discussing above. Despite the fact that the ER system maintains a fairly constant consumption level (with little improvement) it still offers better consumption levels than without an ER device. It is quite clear from Figure 21 that in the case of ER the third membrane appears to be the “cut-off” point as its usefulness beyond this point is clearly limited.

If we compare the levels of power savings allowed by the ER, as in Figure 22, we can see that the combination of both the multiple membrane arrays and the PES allow for such low power consumption rates.

Number of membranes	Power consumption (kWh/m3)	ER Power consumption	Power consumption reduction (kWh/m3)	Increase in efficiency (%)
1	25.519066	4.863826	20.65524	81
2	13.272523	3.423268	9.849255	75
3	9.242331	2.927436	6.314895	68
4	7.272307	2.685065	4.587242	63

Figure 22: Levels of system performance with ER

Ideally we would want a system that included all four membranes and the ER device, but obviously this is not going to be financially viable for such a small-scale operation. In order to determine the best economic option we must examine the costs of each particular system design and compare this with their power consumption level.

Economic Analysis

In order to use an ER device the RO system must have a pumping system, which is capable of positive displacement. Positive displacement allows the intake of the pumps to be regulated according to what is happening downstream of them. In an RO process such as this what this means is that when the ER starts to re-circulate the brine back through the system the HPP and the seawater pump only have to pump what would be considered the permeate flow.

This permeate flow will be very much smaller than the feed flow and so the pumping system doesn't have to work as hard to pump this lower feed flow. By using positive displacement the pumps can slow down thereby causing the reduction in energy consumption. However positive displacement pumps are not cheap and they are rather more expensive than normal pumps. Another factor worth remembering is that the pump capacity for an n-membrane system will always be the same even if the system has ER or not. If the system has ER then it need to get "started-up" and the only way to do this is to pump all of the required flow from the sea. Figures 23 & 24 give a basic breakdown of these costs (costs of the pre-treatment have been omitted because at such a small scale they are relatively insignificant in terms of cost, this is an approach favoured by many when evaluating the capital cost of an RO plant [1].

Number of Membranes	Price of Seawater pump (centrifugal) (£)	Price of HPP (£)	Membrane cost (£)	Total cost (£)
1	1181	530	812	2523
2	1086	530	1624	3240
3	1012	530	2436	3978
4	1012	530	3248	4790

Figure 23: Evaluation of RO costs (no ER)

Number of Membranes	Price of positive displacement pumping system (£)	Price of ER Device (£)	Membrane cost (£)	Total cost (£)	Price differential (£)
1	4491	6720	812	12023	-9500
2	4631	5470	1624	11725	-8485
3	4331	4532	2436	11299	-7321
4	4331	4532	3248	12111	-7321

Figure 24: Evaluation of RO costs with ER

Although other factors such as the manufacturers mark-up on components and materials and labour costs have not been included, it is clear that we can come to a decision without these adding in these overheads (a more comprehensive analysis will have to include these factors, but it has been assumed here that such costs will not differ significantly from design to design an will sufficiently affect our final outcome). The cheapest ER system is around two and half times more expensive than the dearest without ER, this clearly makes for unpleasant reading. However if we now consider the operation of a system during the summer period (we shall assume this to be June 1st – September 30th), using the values of power consumption reduction stated in Figure 22 and assuming that one kWh is equivalent to seven pence, we can calculate the expected economic savings afforded to us through the inclusion of an energy recovery device. Once any possible savings have been determined we can then produce a more realistic indication of the price differentials between a system with RO and one without (see Figure 25 below).

Number of Membranes	Savings over summertime due to lower consumption levels (£)	Cost of system with ER device (£)	Cost of system without RO (£)	Price differential (£)
1	2802	12023	2523	-6698
2	1336	11725	3240	-7149
3	856	11299	3978	-6465
4	603	12111	4790	-6718

Figure 25: Evaluation of savings over summer period

When comparing our new price differential to that of Figure 24 we can see that in some cases the price differential has considerably lowered even after a mere year of operation. RO plants can have an operational history of lasting some twenty years [1], obviously such longevity is desirable but even if our design should only last ten years it is clear that all the ER systems would recoup their initial capital costs.

Of course such an analysis is fraught with inaccuracy. We have not assessed the possible repair costs commonly associated with RO systems (these can be membrane replacement, servicing of pumps and filter replacement) therefore we can expect higher than anticipated running costs. It is also clear that if an RO system were to be implemented on Lundy Island then it would service the island for the whole year and as such potential savings would be higher. Also as a result of the remoteness of the Island we can assume that the cost of electrical energy will be very much higher than 7p/kWh (especially if we use a diesel engine to service the islands needs) this again means that we could expect higher savings. As a consequence of the unreliable nature of the economic study we have been forced to use its results to establish only general conclusions on what we feel is the best route to take.

References

1. www.derwentwatersystems.co.uk/pdfs/sw30hr - 320.pdf

3.2.4 Conclusion of RO analysis

Based on both the above findings it was decided to recommend a single membrane system with ER. Even with a limited number of membranes this option still provides a lower power consumption level than that of MVC (remember we have considered all the pumping aspects for RO whereas with MVC we still need to factor in the pumping requirements).

The main benefits are that we have significantly reduced levels of power consumption and that through time we shall almost certainly regain the initial financial costs through the savings provided by the ER device. The obvious disadvantages of the RO systems are the levels of pre-treatment and supervision required. Research indicates that any potential RO system will suffer from some type of system failure (usually membranes) and it is therefore necessary to have an extensive spare parts inventory.

3.3 Desalination by wind energy

Something that we have not considered up until now is the compatibility of each system with wind energy. As we have previously mentioned Lundy is currently making use of a wind-diesel system. This however is not terribly encouraging, as the diesel engine does not readily lend itself to wind integration [1]; it is not uncommon to have real difficulties with such a set-up.

The idea to use wind power as an energy source for desalination is not new. Wind conditions for example in coastal areas are often in favour of this desalination system. Nonetheless the most challenging problem associated with the implementation of RES-powered desalination plants is the optimum matching of the intermittent RES power output with the steady energy demand for the desalination process. While the wind is relatively predictable it is seldom constant and there will be periods when there will be none at all. The large high frequency component in wind turbulence means that electrical output from a wind turbine will fluctuate quite vigorously in time periods of seconds and minutes. A wind turbine that is meeting a load quite satisfactorily one moment may well fail to meet the load by a large amount, only a matter of seconds or minutes later. Such problems raise the need for either a method of energy storage or a backup supply system. Despite this it must be said that desalination systems driven by wind power are the most frequent renewable energy desalination plants, however practical experience of such schemes is relatively small.

Before any final evaluation is made it is necessary to look at the operational history of combining wind energy with our recommended desalination techniques. The initial intention was to develop a Simulink program (which incidentally was near completion) which would model the power available from the wind against the requirements of the desalination process, but despite there being an active wind turbine on the island there is no recent wind data so any such analysis would have been pointless. Therefore, it is necessary to carry out an evaluation concerning the compatibility of wind energy with our recommended desalination techniques.

Mechanical Vapour Compression

On the island of Rugen in the Baltic Sea, a wind powered seawater desalination plant has been in operation since 1995 [2]. This particular plant deals with the problem of intermittent supply in a rather novel fashion. The compressor speed is directly linked to the wind turbine, such that the increase or decrease of the electric power of the wind energy converter (WEC) will correspond to an equivalent variation of the compressor speed. If however the WEC produces surplus energy, this energy can be used to increase the temperature of the seawater in the evaporator-condenser unit by an electric heater (this holds a special meaning for us if we recall the results of our MVC analysis). Such a combination of a wind turbine and a MVC plant is therefore able to utilise wind energy to a higher degree. If at low wind velocities not enough potable water can be produced using only the electric energy of the WEC, the desalination plant can be operated with additional electric energy from the public electric grid, if available. Also rather than use chemicals in the post-treatment of distillate this particular plant uses ultra-violet light to make sure the distillate is disinfected. The remineralization of the distillate can then be performed by addition of certain minerals.

Other wind energy desalination systems can be found in Egypt, and parts of Europe, in most cases they make use of a “grid” connection. For the operation of a wind-powered desalination plant, it is important to have a plant that is insensitive to repeated start-up and shut down cycles caused by sometimes rapidly changing wind conditions. Typical MVC plants are robust enough to withstand these situations.

Reverse Osmosis

A lot of work has been put into trying to make RO and wind energy compatible with one another, as traditionally the fluctuations inherent with a supply such as wind ruin a process such as RO. An RO plant in Hawaii is currently using a prototype control system, which allows it to cope with the varying nature of wind power [3]. Shown in Figure 26 is a schematic of this system.

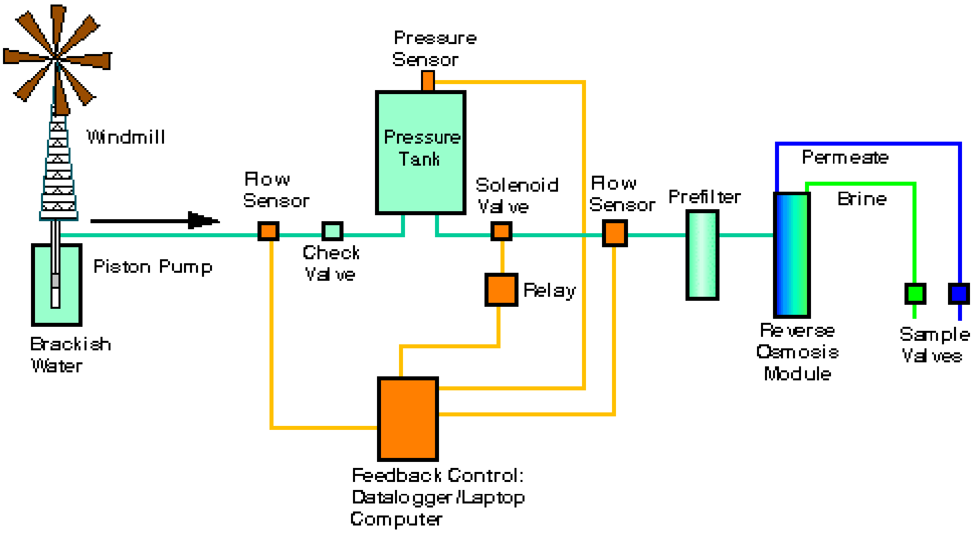


Figure 26: Schematic of prototype RO-Wind plant

A schematic of a wind-powered RO desalination prototype system is shown in Figure 2. Proper operation of the RO module requires that feed water pressure be maintained within a small pre-set range. For the membrane used in this prototype system, the feed water pressure must be maintained in a range of 85 - 105 psi. Feed water pressure equals the water pressure inside the stabilizer, which is continuously monitored by a pressure sensor located on top of the stabilizer. When this pressure is below the minimum value or above the maximum value required for the operation of the RO module, the data logger sends a signal to a solenoid valve to shut down the operation. The purpose of feedback control is to determine inputs to a system necessary to achieve the desired system response. For a wind-powered RO desalination prototype system, the desirable responses are the flow and quality of the permeate from the RO module. The stabilizer and data acquisition devices (including sensors, data logger, and the control computer) constitute the controller.

Naturally the addition of such a feedback system is going to increase the complexity of the system (already a major problem with RO plants), but it seems to be the only suitable method that fully allows the integration of wind energy.

Conclusion

Although both systems discussed offer inventive solutions to the problems posed by the intermittent nature of wind energy they still suffer from fundamental flows when assessed in the context of Lundy Island.

Firstly, the MVC system has a backup grid connection, which is not available on Lundy (instead the backup is provided by a diesel engine). The question therefore arises as to whether it would be better to run a back-up continuously, to make up sudden wind power short – falls, or to run the diesel intermittently in order to minimise fuel consumption. In such situations where the diesel is required to operate on a “stop – start” strategy we are more likely to witness a total collapse of the system frequency and as such system failure. If we then used the option of continuously running the diesel engine it is clear that we would not save much energy and this would negate the entire principle of using a renewable energy source.

On Lundy, to some extent, a “stop – start” policy is operated, it is however not as random as the scenario discussed above. The diesel engine is only automatically started at certain times (7 – 12 am & 4 – 12 pm) during which the island will suffer a brief interruption of supply, as parallel operation is not permitted.

It is clear that the employment of such a strategy would hinder the operation of the MVC system, as it requires a constant rate of power, in its task of meeting the required levels of potable water. The only way to overcome this would be the inclusion of an energy storage device that would help to maintain a constant supply of power; such a device would however significantly increase the capital cost of the plant.

The RO system discussed does, in principle, seem a very exciting prospect, but unfortunately that is all it is. Considerably more research and experimentation in this field is essential before one can begin to even consider implementing such a strategy. The problem with this specific case, and with a similar piece of work on utilising PV technology for desalination [4], is that manufacturers will not guarantee their products if they are to be used out – with the scope of the producers guidelines. The above scheme will operate the pre – treatment system, pumps and membranes at a series of quickly alternating pressures putting great strain upon the system components. Such conditions would prove to be too volatile for any producer as the risk of failure is quite high; this is one of the main reasons why we need more investigation into this area (the project in Hawaii does not discuss failure rates, therefore this theme is very much open to further scrutiny).

Without the above control system, RO generally struggles to deal with an intermittent supply (as mentioned above) and as such we would again need to employ an energy storage device of some kind. Such an addition would clearly affect the low capital cost of an RO plant and would serve to reduce the normal financial benefits that one would associate with RO.

It is therefore clear that the implementation of any wind – powered device is going to require a storage device to act as a back – up, as the current infrastructure on Lundy clearly doesn’t support the proposed set of designs. Therefore we cannot evade the fact that any such undertaking will prove to be significantly more costly than was first expected.

As stated at the beginning, the whole point of conducting a thorough investigation is so it allows us to find out all the small details that are pertinent to establishing our recommendations on the proposed site.

References

1. Freris: "*Wind energy conversion systems*", Prentice Hall (1990), 330 - 356

2. Plantikow, U: *"Wind-powered MVC seawater desalination — operational results"*, Desalination 122 (1999), Issues 2-3, 291 – 299.

3. Liu, C et al: "*Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control*", Desalination, 150 (2002), 277 – 287.

4. www.dti.gov.uk/energy/renewables/publications/pdfs/sp200305.pdf

3.4 Environmental considerations

We have briefly considered some of the possible environmental problems that can arise as a result utilising certain desalination processes, however we have not fully discussed these difficulties.

Mechanical Vapour Compression

The elevated seawater temperature related to the discharge of thermal effluents from desalination schemes are known to impact upon marine organisms in a number of ways with certain communities being particularly affected. For instance, elevated temperatures and increased salinity reduce the overall concentration of dissolved oxygen in the water, which restricts the life forms to those able to exist at low oxygen levels. This effect may be more pronounced if residual concentrations of chemicals are present.

At the level of the individual organism, extreme temperatures may result in death, whilst sub-lethal temperature can modify the rate at which biological processes occur thus influencing movement, the onset of maturity, life stage development, and growth and size. At the species level, excessive temperatures may lead to changes in individual abundance and population diversity [1].

In the context of Lundy Island the above states a very serious case for not using an MVC system. In order to overcome these problems we must select appropriate measures such as the installation of diffusers, which will help considerably to reduce impacts local to the outfall.

Reverse Osmosis

In an RO system drum screens are often provided between the intake structure and feed water pumps in order to prevent flotsam, larger marine organisms and other matter entering the desalination plant pre-treatment system.

Generally the mesh provided on such screens is of the order of 5mm, thus preventing the intake of most fish and other aquatic organisms. However, this abstraction represents two potential sources of impact with these consisting of impingement of fish upon the screens, and entrainment of biota in the feed water system [2].

Also the chemicals used in the plants present a problem, with the chlorine used in the pre-treatment stage presenting a possible harm to human health.

Conclusions

In general MVC will have a greater thermal impact than RO, in terms of both marine and atmospheric discharges. By contrast RO has a greater impact in terms of salt concentration increase in discharged water. Both in their own unique way seem to provide a potential threat to Lundy's Marine Nature Reserve. Naturally the Islanders are both very protective and proud of this site and it seems precautions would have to be taken to dull the possible harmful affects, thus further adding to the capital cost of the plant.

References

1. & 2. Morton. A, et al: "*Environmental impacts of seawater distillation and reverse osmosis processes*", Desalination 108 (1996), 1 – 10

Section Four

Conclusions

4 Conclusions

The overall analysis of Lundy Island has created an impression of how very difficult it is to effectively perform a suitable evaluation. Despite the great detail we have went into in this thesis it seems as though the final decision hinges on two very important parameters – maintenance and reliability.

This was quite a surprise as the original feeling was that energy consumption would dictate the system used, however while energy consumption is still an important factor it is vitally important to fully understand the context of the problem; in our case dealing with the difficulties caused by the remoteness of the region.

Like most other remote regions Lundy is not awash with fully trained engineers who could deal with the problems that can occur when using RO. From the research carried out it seems definite that RO is very demanding in terms of the attention it needs. It requires constant maintenance checks, filter replacement (every couple of months), chemicals to be added to the dosing system, but with MVC we require very little pre and post-treatment and its operational history [1,2] has proven it to be a most reliable process. The island's engineer has to attend to many other matters on the island; it is not possible for him to spend all of his available time maintaining the RO module.

Generally RO has the lower energy consumption of all the desalination systems and here the MATHCAD programs provided similar results, but one eventually begins to realise that this is not the main the consumption difference between the two was not large enough to vindicate the use of an RO system. In an area that was far more accessible then RO would be a far better choice, but in the case of small-scale desalination the keyword is reliability.

The integration of wind also presents more problems for RO, due its rather sensitive nature the system cannot handle the fluctuations common with an energy source such as wind and requires a feedback system to regulate the pressures applied within the system which is quite complex. On the other hand we an MVC employing a most ingenious method of operation, it even allows surplus wind energy to power the auxiliary heater which we have identified as being one of the most important parameters of the MVC system.

In all other sections of evaluation we have found that in this instance MVC is equal to RO and as such the MVC plant would be recommended for use on Lundy.

However if we look carefully at the Lundy problem we can see that the water difficulties only last for around 3 – 4 months. As MVC has no portable format can the initial outlay of an MVC plant be justified if it is only going to be in use for a third of the year?

Whilst the recommendation is technically sound, economics play a major role in such decisions and although a small-scale desalination system is something the island may come to need it seems as though any investment would be put off no other choice is available.

4.1 Further Work

For the continuation of this work it would be good to see the development of a Simulink program, which could analyse both wind and PV energies. Indeed it is possible to set up a data link between the MATHCAD and Simulink packages, this could allow for more complete system analysis as it would allow us to accurately simulate our MATHCAD data against certain time periods (provided our weather data is correct). Such a system would give us real evidence as to whether a certain area could sustain a desalination plant through using renewable energies. Perhaps in future specific areas could be chosen which offer the opportunity to gather more data about the local environment so as to make the design process more rewarding.

It is necessary to make some alterations to the MVC MATHCAD program; it may prove to be more beneficial if the program has a limit placed upon the effectiveness value of the feed heat exchangers as opposed to using a "trial and error" method to ensure the effectiveness is below 85%. It is also possible that the MVC program could incorporate the pumping required for such a system so as to give a more realistic value for the designs power consumption.

Modifications may also be made to the selection process to highlight the vital importance of the reliability of the design; such changes would make the entire system more user friendly.

Section Five

Appendices

5.1 Appendix 1: MVC MATHCAD program

SUMMER CALCULATIONS: 50ºC

For summer calculations it is assumed that 80 residents are on the island and therefore the consumption of water in a typical day will be on average 15 cubic metres. Throughout this period the temperature of seawater is taken as 15 degrees Celsius.

$M_{required} := 15.5\frac{m^3}{day}$		Distillate water required per day
$\rho_{seawater} := 1025\frac{kg}{m^3}$		Density of seawater
$F_{required} := M_{required}\cdot\rho_{seawater}$		Calculation of required feed flow
$F_{required} = 0.183883\,kg\,s^{-1}$		Required seawater feed flow to satisfy demand
$R := 0.35$		Assumed recovery rate of distillate from seawater feed
$F := \frac{F_{required}}{R}$	$F = 0.52538\frac{kg}{s}$	Seawater feed flow rate per second
$D := R\cdot F$	$D = 0.183883\frac{kg}{s}$	Calculates the amount of distillate produced by the MVC system
$B := F - D$	$B = 0.341497\frac{kg}{s}$	Calculates the amount of brine produced as a result of incomplete recovery
$\gamma := 1.32$		Isentropic compressibility factor

$r_p := 1.3$ Compression ratio

$\eta_{comp} := 0.85$ Mechanical compressor efficiency

$C_{p1} := 3930 \cdot \frac{J}{kg \cdot K}$ Assume specific heats of the feed F, distillate D, and the brine B are considered constant and equal to Cp1

$C_{p2} := 1900 \cdot \frac{J}{kg \cdot K}$ Specific heat of the compressed vapour

$L_{vapour} := 2376.1 \cdot 10^3 \cdot \frac{J}{kg}$ Latent heat of evaporated vapour (assumed equal to the latent heat of the condensed vapour)

$v_1 := 12.04 \frac{m^3}{kg}$ Specific volume at entry to evaporator

$U_b := 1.5 \cdot \frac{kW}{m^2 \cdot K}$ $U_d := 1.8 \cdot \frac{kW}{m^2 \cdot K}$ Overall heat transfer coefficients for brine and distillate respectively

$P_e := 12330 \frac{N}{m^2}$ Pe equals pressure at entry to the evaporator

$P_h := r_p \cdot P_e$ $P_h = 1.6029 \times 10^4 \frac{N}{m^2}$ Ph equals pressure at compressor exit

$T_1 := 288 \cdot K$ Temperature of seawater feed

$T_2 = T_f$ Temperature of feed after preheating

$T_3 := 323 \cdot K$ Boiling temperature at evaporator pressure Pe

$T_4 := T_3 \cdot \left(\frac{P_h}{P_e}\right)^{\frac{\gamma - 1}{\gamma}}$ $T_4 = 344.211324 K$ Ideal compressor exit temperature

The following are coefficients required for mathematical proof (Appendix 2)

$$T_{4act} := \left(\frac{T_4 - T_3}{\eta_{comp}}\right) + T_3$$

$T_{4act} = 347.954498\,\mathrm{K}$

Actual temperature at compressor exit due to inherent inefficiency

$T_5 := 328.3456938\,\mathrm{K}$

Temperature of distillate at condenser exit

$T_6 = T_8 = T_0$

Exit temperature of brine and distillate from process

$T_7 := T_3$

Temperature of brine at brine blow down from evaporator

$$T_f := T_3 - \frac{\left[D\cdot C_{p2}\cdot\left(T_{4act} - T_5\right)\right]}{F\cdot C_{p1}}$$

$T_f = 319.681971\,\mathrm{K}$

Calculates the theoretical value of feed temperature required so that heat addition from condensate can take place with need for auxiliary heat addition.

$$\alpha := \frac{1}{\left[\left[1 + \left(\frac{F}{D} - 1\right)^{-1}\right]\cdot\left[1 + \left[\left(\frac{T_3 - T_1}{T_5 - T_3}\right) - \frac{D}{F}\right]^{-1}\right]\right]}$$

Fraction of feed preheated by the brine

$\alpha = 0.559689$

$$T_{01} := T_3 - \alpha\cdot\frac{F}{B}\cdot\left(T_f - T_1\right)$$

$T_{01} = 295.719938\,\mathrm{K}$

Calculates the theoretical exit temperature for brine

$$T_{02} := T_5 - (1 - \alpha)\cdot\frac{F}{D}\cdot\left(T_f - T_1\right)$$

$T_{02} = 288.48875\,\mathrm{K}$

Calculates the theoretical exit temperature for distillate

$$\Delta T := \frac{(T_3 - T_1)}{K}$$

$\Delta T = 35$

$$k_1 := \frac{(T_3 - T_1)}{(T_5 - T_3)}$$

$k_1 = 6.547326$

$$k_2 := \frac{C_{p2}}{C_{p1}} \cdot \frac{(T_{4act} - T_5)}{K}$$

$k_2 = 9.480084$

$$k_3 := \frac{(T_5 - T_3)}{K}$$

$k_3 = 5.345694$

If traditional assumptions are true (see MVC section) then the following will also be true (See Appendix A for full mathematical solution)

$$\beta := \begin{bmatrix} \Delta T \\ \left[-\Delta T - (k_2 + k_3)\cdot(k_1 + 1) + k_2 \cdot k_1\right] \\ \left[(k_2 + k_3) + (k_2 + k_3)\cdot(k_1 + 1) - k_2 \cdot (k_1 + 1)\right] \\ -k_3 \end{bmatrix}$$

As such it is possible to define what recovery ratio is necessary to meet these assumed conditions

$$R_{theory} := \text{polyroots}(\beta) \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$R_{theory} = 0.765281$

$$T_{f2} := T_3 - R_{theory} \cdot \frac{C_{p2}}{C_{p1}} \cdot (T_{4act} - T_5)$$

Calculates what we can expect to be the actual value for the feed temperature under ideal recovery rates

$T_{f2} = 315.74507K$

$Q_x := F \cdot C_{p1} \cdot (T_3 - T_{f2}) - D \cdot C_{p2} \cdot (T_{4act} - T_5)$

Calculates the auxiliary heat required to compensate for difference between the theoretical feed temperature and the real feed temperature

$Q_x = 8.128694 \times 10^3 \, W$

$T_{Bexit} := T_3 - \alpha \cdot \frac{F}{B} \cdot (T_{f2} - T_1)$ $T_{Bexit} = 299.109843 \, K$

$T_{Dexit} := T_5 - (1 - \alpha) \cdot \frac{F}{D} \cdot (T_{f2} - T_1)$ $T_{Dexit} = 293.441498 \, K$

$T_{f3} := T_{f2}$

Feed Heat Exchanger Analysis

1. Brine Feed Heater

Temperature of a*feed at exit from brine feed heater

$T_{fb} := T_{f3}$ $T_{fb} = 315.745077 \, K$

Calculation of effectiveness of heat exchanger based on the heat exchange of brine flow to a*feed flow

$B = 0.3414977 \, kg \, s^{-1}$

$\alpha \cdot F = 0.2940494 \, kg \, s^{-1}$

$Q_{max} := \alpha \cdot F \cdot C_{p1} \cdot (T_7 - T_1)$ $Q_{max} = 4.04465 \times 10^4 \, W$

$Q_1 := \alpha \cdot F \cdot C_{p1} \cdot (T_{fb} - T_1)$ $Q_1 = 3.20626 \times 10^4 \, W$

$\varepsilon_b := \frac{Q_1}{Q_{max}}$ $\varepsilon_b = 0.792716$

Calculation of LMTD for brine heat exchanger

$T_{f1bi} := T_3$ $T_{f1bo} := T_{Bexi}$ $T_{f2bi} := T_1$ $T_{f2bo} := T_{fb}$

$\Delta T_{ab} := T_{f1bi} - T_{f2bo}$ $\Delta T_{ab} = 7.25493 K$

$\Delta T_{bb} := T_{f1bo} - T_{f2bi}$ $\Delta T_{bb} = 11.109843 K$

$\Delta T_{mb} := \frac{\Delta T_{bb} - \Delta T_{ab}}{\ln\left(\frac{\Delta T_{bb}}{\Delta T_{ab}}\right)}$ $\Delta T_{mb} = 9.045901 K$

Using above data it is possible to now calculate the required area for Brine Heat Exchanger

$A_b := \frac{Q_1}{U_b \cdot \Delta T_{mb}}$ $A_b = 2.362956 m^2$

2. Distillate Feed Heater

Temperature of (1-a)*feed at exit from distillate feed heater

$T_{fd} := T_{f3}$ $T_{fd} = 315.74507 K$

Calculation of effectiveness of heat exchanger based on the heat exchange of distillate flow to (1-a)*feed flow

$D = 0.183883 kg\, s^{-1}$

$(1 - \alpha) \cdot F = 0.231331 kg\, s^{-1}$

$Q_{max2} := D \cdot C_{p1} \cdot (T_5 - T_1)$ $Q_{max2} = 2.915624 \times 10^4 W$

$Q_2 := (1 - \alpha)\cdot F\cdot C_{p1}\cdot(T_{fd} - T_1)$ $Q_2 = 2.522389\times 10^4\,W$

$\varepsilon_d := \dfrac{Q_2}{Q_{max2}}$ $\varepsilon_d = 0.865128$

Calculation of LMTD for distillate heat exchanger

$T_{f1di} := T_5$ $T_{f1do} := T_{Dexit}$ $T_{f2di} := T_1$ $T_{f2do} := T_{fd}$

$\Delta T_{ad} := T_{f1di} - T_{f2do}$ $\Delta T_{ad} = 12.600623K$

$\Delta T_{bd} := T_{f1do} - T_{f2di}$ $\Delta T_{bd} = 5.441498K$

$\Delta T_{md} := \dfrac{\Delta T_{bd} - \Delta T_{ad}}{\ln\left(\dfrac{\Delta T_{bd}}{\Delta T_{ad}}\right)}$ $\Delta T_{md} = 8.525896K$

Using above data it is possible to now calculate the required area for Distillate Heat Exchanger

$A_d := \dfrac{Q_2}{U_d\cdot\Delta T_{md}}$ $A_d = 1.643613m^2$

Evaporator/Condenser Analysis

Calculation of heat transfer coefficient of evaporator/condenser

$T_z := \dfrac{T_3 - 273K}{1\cdot K}$

$k := 1.9695 + 1.2057\cdot 10^{-2}\cdot T_z - 8.5989\cdot 10^{-5}\cdot T_z^{\,2} + 2.565\cdot 10^{-7}\cdot T_z^{\,3}$

$U_{evap} := k\cdot\dfrac{kW}{m^2\cdot K}$ $U_{evap} = 2.38944\dfrac{kW}{m^2\cdot K}$

Calculation of LMTD for evaporator/condenser

$T_{f1condin} := T_{4act}$ $T_{f1condout} := T_5$ $T_{f2evapin} := T_f$ $T_{f2evapout} := T_3$

$\Delta T_{aevap} := T_{f1condin} - T_{f2evapout}$ $\Delta T_{aevap} = 24.954498\,K$

$\Delta T_{bevap} := T_{f1condout} - T_{f2evapin}$ $\Delta T_{bevap} = 8.663723\,K$

$\Delta T_{mevap} := \dfrac{\Delta T_{bevap} - \Delta T_{aevap}}{\ln\left(\dfrac{\Delta T_{bevap}}{\Delta T_{aevap}}\right)}$ $\Delta T_{mevap} = 15.399025\,K$

Calculation of heat required by evaporator to raise feed temperature to T3 and to evaporate D

$Q_{evap} := F \cdot C_{p1} \cdot \left(T_3 - T_f\right) + D \cdot L_{vapour}$ $Q_{evap} = 4.437755 \times 10^{5}\,W$

Using above data it is possible to now calculate the required area for the evaporator

$A_{evap} := \dfrac{Q_{evap}}{\Delta T_{mevap} \cdot U_{evap}}$ $A_{evap} = 12.060741\,m^{2}$

Compressor Analysis

Calculation of energy required by compressor per kg of distillate

$$W_{comp} := \frac{1}{\left(\eta_{comp}\right)} \cdot \frac{\gamma}{\gamma - 1} \cdot P_e \cdot v_1 \cdot \left[\left(\frac{P_h}{P_e}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right]$$

$W_{comp} = 4.731075 \times 10^{4}\,\frac{J}{kg}$

Calculation of power consumption (for entire MVC system) per cubic metre of distillate

$\rho_{distillate} := 1025\frac{kg}{m^3}$

$P_{compressor} := W_{comp} \cdot \rho_{distillate}$

$P_{compressor} = 13.470422\frac{kW \cdot hr}{m^3}$

5.2 APPENDIX 2: MVC proof

The following proof is based on the equations discussed in section 3.1.2 and aims to calculate the required recovery rate which allows this set of equations to be true. As a consequence we shall prove that the general assumptions used in designing an MVC system are incorrect.

Firstly we must rearrange our equations so that they all have the common term R

Then $D = R \cdot F$ and also $B = F - D$ therefore

Equation 1 now becomes $T_f := T_3 - R \cdot \left[\frac{C_{p2} \cdot (T_{4act} - T_5)}{C_{p1}} \right]$

Equation 5 can be arranged to give $T_0 = T_1 + T_3 - T_f + R \cdot (T_5 - T_3)$

If we substitute the value the value of Tf equation 5 now becomes

$$T_0 = T_1 + R \cdot \left[\frac{C_{p2} \cdot (T_{4act} - T_5)}{C_{p1}} \right] + R \cdot (T_5 - T_3)$$

This therefore gives us

$$T_0 = T_1 + R \cdot \left[(T_5 - T_3) + \left[\frac{C_{p2} \cdot (T_{4act} - T_5)}{C_{p1}} \right] \right]$$

Equation 3 now becomes $T_0 := T_3 - \alpha \cdot \frac{1}{(1 - R)} \cdot (T_f - T_1)$

which can be rearranged to allow $\alpha = (1 - R) \cdot \frac{(T_3 - T_0)}{(T_f - T_1)}$

If we substitute our values for equations 1 and 5 we now have

$$\alpha = (1 - R)\cdot\frac{\left[T_3 - \left[T_1 + R\cdot\left[\left(T_5 - T_3\right) + \left[\frac{C_{p2}\cdot\left(T_{4act} - T_5\right)}{C_{p1}}\right]\right]\right]\right]}{\left[T_3 - R\cdot\left[\frac{C_{p2}\cdot\left(T_{4act} - T_5\right)}{C_{p1}}\right] - T_1\right]}$$

It is quite obvious that in order to make the assessment easier we must somehow simplify the above equation, this can be done if one assumes that any MVC system operating at a constant evaporator temperature and a constant compression ratio this therefore means that our operating limits (i.e. T5 etc) will always remain constant. As such we can treat some of the variable in the above equation as constant and use a single term to signify many, therefore:

$$\Delta T = \left(T_3 - T_1\right)$$

$$k_1 = \frac{\left(T_3 - T_1\right)}{\left(T_5 - T_3\right)}$$

$$k_2 = \frac{C_{p2}}{C_{p1}}\cdot\left(T_{4act} - T_5\right)$$

$$k_3 = \left(T_5 - T_3\right)$$

Therefore we now have

$$\alpha = (1 - R)\cdot\left[\frac{\left[\Delta T - R\cdot\left(k_2 + k_3\right)\right]}{\left(\Delta T - k_2\cdot R\right)}\right]$$

It is also possible to rearrange equation 2 (see page 41), this gives us

$$\alpha^{-1} = \frac{R^{-1}\cdot\left(k_1 + 1\right) - 1}{k_1\cdot R^{-1} - \left(k_1 + 1\right) + R}$$

If we now set these two equations equal to one another we get

$$(1 - R)\cdot\left[\frac{\left[\Delta T - R\cdot\left(k_2 + k_3\right)\right]}{\left(\Delta T - k_2\cdot R\right)}\right] = \frac{\left[k_1\cdot R^{-1} - \left(k_1 + 1\right) + R\right]}{\left[R^{-1}\cdot\left(k_1 + 1\right) - 1\right]}$$

Now that we have established the common factor R it is simply a (lengthy) process of multiplying out which will eventually gives us:

$$0 = \Delta T + R\cdot\left[-\Delta T - \left(k_2 + k_3\right)\cdot\left(k_1 + 1\right) + k_2\cdot k_1\right] + R^2\cdot\left[\left(k_2 + k_3\right) + \left(k_2 + k_3\right)\cdot\left(k_1 + 1\right) - k_2\left(k_1 + 1\right)\right] + R^3\cdot\left(-k_3\right)$$

We have achieved what we set out to do (establishing an equation in terms of R), this equation will allow for the solution of the recovery rate for any MVC design (within the previously stated assumptions).

By entering the coefficients into MATHCAD we can solve this polynomial equation(see Appendix 1). The calculation of this theoretical value of R is given in the MVC program in order to prove that the previous design assumptions are incorrect.

5.3 Appendix 3: MVC Summer results (rp=1.3)

	50	55	60	65	70	75	80	85
R theory	0.76528	0.78820	0.80596	0.82063	0.83290	0.84338	0.85239	0.8602
R system	0.35	0.3605	0.3686	0.3753	0.3809	0.3857	0.3894	0.3934
Tf1 (K)	319.681	324.547	329.416	334.2966	339.1861	344.084	348.992	353.896
Tf2 (K)	315.2	319.5	323.8	328	332	336.6	340.8	345.2
Qx (kW)	9.249	10.113	11	12.118	13.627	14.016	15.197	15.96
T01 (K)	295.7199	296.0965	296.457	296.8036	297.135	297.464	297.7812	298.101
Tb exit (K)	299.579	300.503	301.412	302.407	303.574	304.207	305.1981	306.00
T02 (K)	288.488	288.746	288.956	289.1291	289.275	289.398	289.4847	289.598
Td exit (K)	294.127	294.9318	295.704	296.58	297.676	298.062	298.8931	299.515
Eb (%)	77.71	78.75	79.55	80	80	81	81.23	81.71
Ab (m2)	2.1897	2.264	2.332	2.364	2.346	2.458	2.479	2.531
Ed (%)	84.813	84.776	84.81	84.655	84.166	84.828	84.77	84.99
Ad (m2)	1.4934	1.5385	1.5811	1.599	1.583	1.668	1.683	1.725
Q evap (kW)	443.566	441.412	439.276	437.12	434.944	432.82	430.386	428.43
A evap (m2)	12.055	11.5863	11.1553	10.757	10.391	10.048	9.723	9.426
W comp (kJ/kg)	47.31	48.045	48.742	49.425	50.098	50.77	51.4377	52.093
P comp (kWh/m3)	13.470	13.679	13.878	14.072	14.2642	14.457	14.645	14.832

5.4 Appendix 4: MVC Summer results (rp=1.2)

	50	55	60	65	70	75	80	85
R theory	0.8299	0.84775	0.8612	0.87243	0.8816	0.8894	0.896149	0.9019
R system	0.35	0.3605	0.3675	0.37531	0.3809	0.3857	0.38984	0.3934
Tf1 (K)	320.706	325.614	330.319	335.450	340.777	345.310	350.247	355.187
Tf2 (K)	315	320	324.4	328.6	332.9	337	341.3	345.5
Qx (kW)	11.78	10.9852	12.062	13.3772	14.18	15.562	16.57777	17.786
T01 (K)	293.460	293.7323	293.969	294.221	294.4500	294.689	294.919	295.1435
Tb exit (K)	298.613	298.841	299.6	300.634	301.386	302.420	303.267	304.206
T02 (K)	288.029	288.223	288.347	288.502	288.68	288.694	288.767	288.831
Td exit (K)	294.761	294.725	295.342	296.349	296.975	297.928	298.6522	299.4808
Eb (%)	77.14	80	80.889	81	81.6364	81.6667	82	82.143
Ab (m2)	2.359964	2.6005	2.761	2.724	2.792	2.7669	2.796	2.798
Ed (%)	82.49	84.6	84.973	84.55	84.84	84.577	84.68	84.03
Ad (m2)	1.4256	1.61	1.71	1.71	1.7625	1.7543	1.78355	1.79322
Q evap (kW)	441.661	428.757	437.09	434.8977	432.685	430.525	428.053	426.059
A evap (m2)	17.506	16.392	16.157	15.556	15.013	14.5058	14.0237	13.588
W comp (kJ/kg)	32.5568	33.0622	33.542	34.0011	34.4755	34.942	35.396	35.8475
P comp (kWh/m3)	9.269	9.4135	9.5502	9.68387	9.5765	9.7059	10.0782	10.2066

5.5 Appendix 5: MVC Summer results (rp=1.1)

	50	55	60	65	70	75	80	85
R theory	0.907	0.9173	0.925	0.9313	0.9364	0.9408	0.945	0.9477
R system	0.35	0.3539	0.3569	0.35938	0.36134	0.363	0.3644	0.36568
Tf1 (K)	321.802	326.7786	331.751	336.725	341.70	346.677	351.561	356.632
Tf2 (K)	316.4	320.8	324.9	328.8	333	337.5	341.9	345.6
Qx (kW)	11.155	11.908	13.5338	15.928	17.3919	18.26	17.9	21.27119
T01 (K)	290.886	290.992	291.099	291.206	291.308	291.413	291.610	291.6211
Tb exit (K)	296.019	296.698	297.6609	298.817	299.683	300.264	300.941	302.291
T02 (K)	287.867	287.871	287.871	287.865	287.8566	287.841	288.308	287.805
Td exit (K)	293.772	294.348	295.244	296.350	297.1323	297.593	298.486	299.4665
Eb (%)	81.1429	82	82	81.6	81.81	82.5	82.923	82.29
Ab (m2)	3.312	3.388	3.379	3.3679	3.41	3.55	3.27	3.41
Ed (%)	84.31	84.87	84.57	83.95	84	84.575	84.412	84.15
Ad (m2)	1.778	1.823236	1.814	1.803	1.824	1.907	1.919	1.829
Q evap (kW)	439.396	486.91	493.970	500.892	495.34	514.586	521.29	515.053
A evap (m2)	33.9098	31.8444	30.6885	30.3377	29.319	28.3615	27.149	25.976
W comp (kJ/kg)	16.8398	17.10121	17.349	17.592	17.83224	18.0733	18.309	18.54191
P comp (kWh/m3)	4.795	4.869	4.939	5.009	4.953	5.1458	5.2129	5.151

5.6 Appendix 6: MVC Winter results (rp=1.1)

	50	55	60	65	70	75	80	85
R theory	0.9235	0.930572	0.935986	0.954928	0.944327	0.947021	0.95047	0.9529
R system	0.35	0.35	0.3547	0.362	0.35784	0.3591	0.36015	0.36113
Tf1 (K)	321.802	326.792	331.758	336.715	341.712	346.691	351.671	356.649
Tf2 (K)	315.1	319.3	323.5	327.7	331.8	336	340.2	344.8
Qx (kW)	4.11	4.6	4.99	5.34	5.94	6.385	6.83	6.865
T01 (K)	282.907	282.997	283.10	283.229	283.308	283.410	283.512	283.614
Tb exit (K)	289.336	290.203	291.068	291.936	292.897	293.765	294.634	295.113
T02 (K)	279.827	279.767	279.802	279.889	279.767	279.744	279.718	279.693
Td exit (K)	287.040	287.791	288.602	289.450	290.262	291.037	291.809	292.162
Eb (%)	81.62	81.875	82.076	82.2414	82.222	82.35	82.466	83.07
Ab (m2)	1.039	1.0641	1.0626	1.0459	1.0687	1.0759	1.0824	1.09786
Ed (%)	84.28	84.38	84.346	84.2577	84.2371	84.2748	84.3097	84.8628
Ad (m2)	0.54198	0.55016	0.5544	0.5566	0.5576	0.5617	0.5654	0.5750
Q evap (kW)	130.4	129.747	129.092	128.431	127.765	127.115	126.372	122.7
A evap (m2)	10.064	9.7045	9.3446	8.997	8.7189	8.4352	8.163	7.723
W comp (kJ/kg)	16.839	17.1012	17.3494	17.592	17.8322	18.073	18.3087	18.5419
P comp (kWh/m3)	4.794	4.86909	4.9397	5.009	5.0772	5.1459	5.213	5.279

5.7 Appendix 7: MVC Winter results (rp=1.2)

	50	55	60	65	70	75	80	85
R theory	0.8589	0.87122	0.8809	0.88897	0.89585	0.90182	0.90702	0.912
R system	0.35	0.3549	0.3591	0.36225	0.36505	0.3675	0.3696	0.371455
Tf1 (K)	320.7606	325.654	330.593	335.5394	340.486	345.437	350.390	355.343
Tf2 (K)	314.5	318.5	322.5	327	331.3	335.6	339.8	344
Qx (kW)	3.803	4.3232	4.833	5.056	5.397	5.7409	6.145	6.389
T01 (K)	285.539	285.7549	285.973	286.188	286.396	286.608	286.818	287.026
Tb exit (K)	291.250	292.374	293.496	294.154	294.993	295.8378	296.775	297.712
T02 (K)	279.882	279.815	279.954	279.9649	279.975	279.974	279.967	279.956
Td exit (K)	287.067	288.040	289.066	289.5133	290.1879	291.8588	291.6372	292.4139
Eb (%)	80.232	80.020	80.1887	81.034	81.43	81.76	81.92	82.1
Ab (m2)	0.859	0.851	0.8445	0.882	0.8991	0.913	0.9192	0.9015
Ed (%)	84.96	84.468	84.0711	84.4672	84.843	84.966	84.991	84.9883
Ad (m2)	0.5058	0.499	0.4942	0.5184	0.5292	0.5388	0.5425	0.5325
Q evap (kW)	131.073	130.425	129.779	129.12	128.47	127.8291	127.095	123.41
A evap (m2)	5.19542	4.9988	4.815	4.645	4.487	4.339	4.198	3.971
W comp (kJ/kg)	32.557	33.062	33.542	34.0116	34.475	34.942	35.396	35.847
P comp (kWh/m3)	9.269	9.41	9.550	9.683	9.816	9.9486	10.078	10.206

5.8 Appendix 8: MVC Winter results (rp=1.3)

	50	55	60	65	70	75	80	85
R theory	0.80326	0.819456	0.832244	0.843072	0.852329	0.860381	0.867421	0.873628
R system	0.35	0.357	0.3626	0.3673	0.3726	0.3749	0.3779	0.3807
Tf1 (K)	319.682	324.58	329.474	334.38	339.27	344.194	349.11	354.029
Tf2 (K)	313.8	318	322.3	326.5	330.8	335	339.2	343.5
Qx (kW)	3.604	3.953	4.243	4.598	4.87	5.26	5.624	5.787
T01 (K)	287.882	288.20	288.52	288.83	289.150	289.444	289.746	290.046
Tb exit (K)	293.088	294.077	294.971	295.955	296.845	297.83	298.8167	299.711
T02 (K)	280.187	280.335	280.4641	280.5659	280.716	280.724	280.778	280.831
Td exit (K)	287.325	288.188	288.912	289.741	290.489	291.265	292.071	292.766
Eb (%)	78.6	79.166	79.8113	80.1724	80.635	80.8824	81.0959	81.41
Ab (m2)	0.72	0.7327	0.7516	0.761	0.7717	0.7823	0.7883	0.779
Ed (%)	84.847	84.7	84.82	84.76	84.822	84.84	84.82	84.94
Ad (m2)	0.464	0.471	0.483	0.4887	0.4975	0.503	0.5073	0.5026
Q evap (kW)	131.7	131.06	130.427	129.787	129.14	128.511	127.78	124.104
A evap (m2)	3.5793	3.445	3.3209	3.205	3.096	2.997	2.901	2.745
W comp (kJ/kg)	47.31	48.045	48.74	49.425	50.11	50.77	51.44	52.093
P comp (kWh/m3)	13.47	13.679	13.878	14.072	14.264	14.457	14.65	14.832

5.9 Appendix 9: RO MATHCAD program

SUMMER CALCULATIONS

For summer calculations it is assumed that 80 residents are on the island and therefore the consumption of water in a typical day will be on average 15.5 cubic metres. Throughout this period the temperature of seawater is taken as 15 degrees celcius.

$c := 1.1\cdot\frac{mole}{liter}$

Typical ionic salt concentration of seawater

$R := 0.082\cdot\frac{liter\cdot 1\cdot 10^{5}\cdot N}{K\cdot mole\cdot m^{2}}$

Gas Constant

$T_{sea} := 288\cdot K$

Temperature of seawater

$P_{sea} := c\cdot R\cdot T_{sea}$ $\quad P_{sea} = 2.59776\times 10^{6}\,\frac{N}{m^{2}}$

Osmotic pressure of seawater at temperature Tsea

$P_{seawater} := 300000\frac{N}{m^{2}}$

Pressure generated by seawater pump

$P_{pump} := 5520000\frac{N}{m^{2}}$

Pressure generated by high pressure pump

$P_{PXBoost} := 350000\frac{N}{m^{2}}$

Pressure form HP pump to compensate for pressure losses (energy recovery only)

$m_{required} := 15.5\frac{m^{3}}{day}$ $\quad m_{required} = 0.645833\,m^{3}\,\frac{1}{hr}$

$\eta_{m} := 0.9$

Efficiency of motor used to power pumps

$\eta_{seapump} := 0.88$ Efficiency of seawater pump

$\eta_{PXB} := 0.70$ Efficiency of circulation pump

$\eta_{pump} := 0.85$ Efficiency of high pressure pump

$\eta_{er} := 0.95$ Efficiency of energy recovery device

1a: Single Membrane System (no energy recovery)

$\alpha := 0.08$ Rate of recovery of permeate from seawater feed

$$m_{feed} := \frac{m_{required}}{\alpha}$$

$m_{feed} = 8.072917 m^3 \frac{1}{hr}$ Required seawater feed to satisfy demand

$$m_{permeate} := \alpha \cdot m_{feed}$$

$m_{permeate} = 0.645833 m^3 \frac{1}{hr}$ Permeate water from single membrane

$$K_f := \frac{m_{permeate}}{\left(\frac{P_{pump} - P_{sea}}{1 \cdot 10^5}\right)}$$

$K_f = 6.139063 \times 10^{-6} \frac{m^4 s}{kg}$ Calculation of flow rate factor of membrane

Calculation of power consumption (for single membrane) per cubic metre

$$P_{pump1} := \frac{P_{pump} \cdot m_{feed}}{\eta_{pump} \cdot \eta_m}$$

$P_{pump1} = 1.565904 \times 10^4 W$

$$P_{seawater1} := \frac{P_{seawater} \cdot m_{feed}}{\eta_{seapump} \cdot \eta_m}$$

$P_{seawater1} = 822.022306 W$

$P_{total} := P_{pump1} + P_{seawater1}$ $P_{total} = 1.648106\times 10^{4}\ W$

$P_{consumption} := \frac{P_{total}}{m_{permeate}}$ $P_{consumption} = 25.519066 \frac{kW\cdot hr}{m^{3}}$

1b: Single Membrane System (with energy recovery)

Calculation of power consumption (for single membrane with energy recovery device) per cubic metre

$P_{pumpef} := \frac{P_{pump}\cdot(m_{permeate})}{\eta_{seapump}\cdot\eta_{m}}$ $P_{pumpef} = 1.210017\times 10^{3}\ W$

$P_{PXB} := \frac{P_{PXBoost}\cdot(m_{feed} - m_{permeate})}{\eta_{PXB}\cdot\eta_{m}}$ $P_{PXB} = 1.109182\times 10^{3}\ W$

$P_{totalef} := P_{pumpef} + P_{PXB} + P_{seawater1}$ $P_{totalef} = 3.141221\times 10^{3}\ W$

$P_{consumptionef} := \frac{P_{totalef}}{m_{permeate}}$ $P_{consumptionef} = 4.863826 \frac{kW\cdot hr}{m^{3}}$

2a: Double Membrane System (no energy recovery)

$P_{s2} := P_{sea}\cdot\frac{m_{feed}}{(m_{feed} - m_{permeate})}$

$P_{s2} = 2.823652\times 10^{6} \frac{N}{m^{2}}$ Osmotic pressure in the second membrane

$$m_{permeate2} := K_f \left[\frac{P_{pump}}{\left(1 \cdot 10^5\right)} - \frac{P_{s2}}{\left(1 \cdot 10^5\right)} \right]$$

$m_{permeate2} = 0.59591 m^3 \frac{1}{hr}$

Permeate water flow from the second membrane

$$m_{total} := m_{permeate} + m_{permeate2}$$

$m_{total} = 1.241743 m^3 \frac{1}{hr}$

Combined permeate water flow from membranes 1 & 2

$\alpha_2 := \frac{m_{total}}{m_{feed}}$ $\alpha_2 = 0.153816$

New recovery rate based on m total

At a higher recovery rate it is know possible to reduce the amount of feed water passing through the system

$m_{newfeed} := \frac{m_{required}}{\alpha_2}$ $m_{newfeed} = 4.198742 m^3 \frac{1}{hr}$

Based on our new feed flow rate we must remember to recalculate the new total flow rate (as a way of checking the correctness of this calculation, any new value for permeate flow should always equal the original)

$m_{totalnew} := m_{newfeed} \cdot \alpha_2$ $m_{totalnew} = 0.645833 m^3 \frac{1}{hr}$

Calculation of power consumption (for double membrane) per cubic metre

$P_{pump2} := \frac{P_{pump} \cdot m_{newfeed}}{\eta_{pump} \cdot \eta_m}$ $P_{pump2} = 8.144302 \times 10^3 W$

$P_{seawater2} := \frac{P_{seawater} \cdot m_{newfeed}}{\eta_{seapump} \cdot \eta_m}$ $P_{seawater2} = 427.535626 W$

$P_{total2} := P_{pump2} + P_{seawater2}$ $P_{total2} = 8.571838 \times 10^3 W$

$$P_{consumption2} := \frac{P_{total2}}{m_{totalnew}}$$

$$P_{consumption2} = 13.272523 \frac{kW \cdot hr}{m^3}$$

2b: Double Membrane System (with energy recovery)

Calculation of power consumption (for double membrane with energy recovery device) per cubic metre

$$P_{pumpef2} := \frac{P_{pump} \cdot m_{totalnew}}{\eta_{pump} \cdot \eta_m}$$

$$P_{pumpef2} = 1.252723 \times 10^3 \, W$$

$$P_{PXB2} := \frac{P_{PXBoost} \cdot (m_{newfeed} - m_{totalnew})}{\eta_{PXB} \cdot \eta_m}$$

$$P_{PXB2} = 530.601634 W$$

$$P_{totalef2} := P_{pumpef2} + P_{PXB2} + P_{seawater2}$$

$$P_{totalef2} = 2.210861 \times 10^3 \, W$$

$$P_{consumptionef2} := \frac{P_{totalef2}}{m_{totalnew}}$$

$$P_{consumptionef2} = 3.423268 \frac{kW \cdot hr}{m^3}$$

3a: Triple Membrane System (no energy recovery)

$$P_{s3} := P_{sea} \cdot \frac{m_{feed}}{(m_{feed} - m_{total})}$$

$$P_{s3} = 3.06997 \times 10^6 \, Pa$$

Osmotic pressure in the third membrane

$$m_{permeate3} := K_f \left[\frac{P_{pump}}{(1 \cdot 10^5)} - \frac{P_{s3}}{(1 \cdot 10^5)} \right]$$

$m_{permeate3} = 0.541472 m^3 \frac{1}{hr}$

Permeate water flow from the third membrane

$m_{total2} := m_{permeate} + m_{permeate2} + m_{permeate3}$

$m_{total2} = 1.783215 m^3 \frac{1}{hr}$

Combined permeate water flow from membranes 1, 2 & 3

$\alpha_3 := \frac{m_{total2}}{m_{feed}}$

$\alpha_3 = 0.220889$

New recovery rate based on m total2

At a higher recovery rate it is know possible to reduce the amount of feed water passing through the system

$m_{newfeed2} := \frac{m_{required}}{\alpha_3}$

$m_{newfeed2} = 2.923797 m^3 \frac{1}{hr}$

$m_{totalnew2} := m_{newfeed2} \cdot \alpha_3$

$m_{totalnew2} = 0.645833 m^3 \frac{1}{hr}$

Calculation of power consumption (for triple membrane) per cubic metre

$P_{pump3} := \frac{P_{pump} \cdot m_{newfeed2}}{\eta_{pump} \cdot \eta_m}$

$P_{pump3} = 5.671291 \times 10^3 W$

$P_{seawater3} := \frac{P_{seawater} \cdot m_{newfeed2}}{\eta_{seapump} \cdot \eta_m}$

$P_{seawater3} = 297.714752 W$

$P_{total3} := P_{pump3} + P_{seawater3}$

$P_{total3} = 5.969006 \times 10^3 W$

$$P_{consumption3} := \frac{P_{total3}}{m_{totalnew2}}$$

$$P_{consumption3} = 9.242331 \frac{kW \cdot hr}{m^3}$$

3b:Triple Membrane System (with energy recovery)

Calculation of power consumption (for triple membrane with energy recovery device) per cubic metre

$$P_{pumpef3} := \frac{P_{pump} \cdot m_{totalnew2}}{\eta_{pump} \cdot \eta_m}$$

$$P_{pumpef3} = 1.252723 \times 10^3 \, W$$

$$P_{PXB3} := \frac{P_{PXBoost} \cdot (m_{newfeed2} - m_{totalnew2})}{\eta_{PXB} \cdot \eta_m}$$

$$P_{PXB3} = 340.197685 W$$

$$P_{totalef3} := P_{pumpef3} + P_{PXB3} + P_{seawater3}$$

$$P_{totalef3} = 1.890636 \times 10^3 \, W$$

$$P_{consumptionef3} := \frac{P_{totalef3}}{m_{totalnew2}}$$

$$P_{consumptionef3} = 2.927436 \frac{kW \cdot hr}{m^3}$$

4a: 4* Membrane System (no energy recovery)

$$P_{s4} := P_{sea} \cdot \frac{m_{feed}}{(m_{feed} - m_{total2})}$$

$$P_{s4} = 3.33426 \times 10^6 \, Pa$$

Osmotic pressure in the fourth membrane

$$m_{permeate4} := K_f \left[\frac{P_{pump}}{(1 \cdot 10^5)} - \frac{P_{s4}}{(1 \cdot 10^5)} \right]$$

$$m_{permeate4} = 0.483062 m^3 \frac{1}{hr}$$

Permeate water flow from the fourth membrane

$m_{total3} := m_{permeate} + m_{permeate2} + m_{permeate3} + m_{permeate4}$

$m_{total3} = 2.266277\,m^{3}\,\frac{1}{hr}$

Combined permeate water flow from membranes 1, 2,3 & 4

$\alpha_4 := \frac{m_{total3}}{m_{feed}}$

$\alpha_4 = 0.280726$

New recovery rate based on m total3

At a higher recovery rate it is know possible to reduce the amount of feed water passing through the system

$m_{newfeed3} := \frac{m_{required}}{\alpha_4}$

$m_{newfeed3} = 2.300583\,m^{3}\,\frac{1}{hr}$

$m_{totalnew3} := m_{newfeed3} \cdot \alpha_4$

$m_{totalnew3} = 0.645833\,m^{3}\,\frac{1}{hr}$

Calculation of power consumption (for 4* membrane) per cubic metre

$P_{pump4} := \frac{P_{pump} \cdot m_{newfeed3}}{\eta_{pump} \cdot \eta_m}$

$P_{pump3} = 5.671291 \times 10^{3}\,W$

$P_{seawater4} := \frac{P_{seawater} \cdot m_{newfeed3}}{\eta_{seapump} \cdot \eta_m}$

$P_{seawater4} = 234.256162\,W$

$P_{total4} := P_{pump4} + P_{seawater4}$

$P_{total4} = 4.696698 \times 10^{3}\,W$

$P_{consumption3} := \frac{P_{total4}}{m_{totalnew3}}$

$P_{consumption3} = 7.272307\,\frac{kW \cdot hr}{m^{3}}$

4b: 4* Membrane System (with energy recovery)

Calculation of power consumption (for 4* membrane with energy recovery device) per cubic metre

$$P_{pumpef4} := \frac{P_{pump} \cdot m_{totalnew3}}{\eta_{pump} \cdot \eta_{m}}$$

$$P_{pumpef4} = 1.252723 \times 10^{3}\ W$$

$$P_{PXB4} := \frac{P_{PXBoost} \cdot \left(m_{newfeed3} - m_{totalnew3}\right)}{\eta_{PXB} \cdot \eta_{m}}$$

$$P_{PXB4} = 247.125087\ W$$

$$P_{totalef4} := P_{pumpef4} + P_{PXB4} + P_{seawater4}$$

$$P_{totalef4} = 1.734105 \times 10^{3}\ W$$

$$P_{consumptionef3} := \frac{P_{totalef4}}{m_{totalnew3}}$$

$$P_{consumptionef3} = 2.685065 \frac{kW \cdot hr}{m^{3}}$$

5.10 APPENDIX 10: Summer & Winter RO results

	Summer	Winter
Pos 1 (bar)	25.9776	25.256
Membrane 1 recovery	0.08	0.08
Mass required (m3/hr)	8.072917	2.395833
P normal Consumption1 (kWh/m3)	25.519066	25.519066
Per Consumption1 (kWh/m3)	4.8638	4.8638
Pos 2 (bar)	28.23652	27.452
Membrane 2 recovery	0.153816	0.15133
Mass required 2 (m3/hr)	4.198742	1.243518
P normal Consumption2 (kWh/m3)	13.272523	13.2452
P er Consumption2 (kWh/m3)	3.423268	3.4199
Pos 3 (bar)	30.06997	29.86
Membrane 3 recovery	0.220889	0.221837
Mass required 3 (m3/hr)	2.923797	0.863996
P normal Consumption3 (kWh/m3)	9.242331	9.202803
P er Consumption3 (kWh/m3)	2.927436	2.9226
Pos 4 (bar)	33.3426	32.456
Membrane 4 recovery	0.280726	0.282602
Mass required 4 (m3/hr)	2.300583	0.678222
P normal Consumption4 (kWh/m3)	7.272307	7.22404
P er Consumption4 (kWh/m3)	2.685065	2.679127