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The viability of renewable energy and energy storage as the power source for municipal- scale reverse osmosis desalination

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ABSTRACT

This research investigates the viability of renewable energy and energy storage to meet a significant and fundamental human need (in this case, large-scale drinking water supplies) unassisted by conventional power. The use of renewable energy to power reverse osmosis (RO) desalination plants to provide potable water for around 50,000 people in Newhaven, in South East England, and in Massawa in Eritrea, was investigated. The following energy sources, in a variety of combinations were specifically assessed: (i) wind power, (ii) wave power, (iii) solar power, (iv) tidal current power, (v) hydrogen production, storage and use in Fuel Cells. The following types of RO plants were studied: (i) No Brine Stream Recovery (BSR) RO plant, (ii) Pelton Wheel BSR RO plant, (iii) Pressure Exchanger BSR RO plant. Modelling was conducted to derive the amount of water that each RO plant would deliver from various combinations and amounts of renewable power input, at varying feedwater temperatures. Scenarios that were not able to deliver enough water to meet the users' needs were scaled-up so that they could. The cost of the scaled-up scenarios that were able to meet the users' water demands was compared with the costs associated with the equivalent conventionallypowered scenario over a 25-year life. Specifically, the following were considered: (i) A coal-fired plant with carbon capture and storage (CCS) at Newhaven and (ii) A diesel generator at Massawa. This comparison was made with and without the external costs associated with conventional energy production and use.

Keywords: Reverse osmosis desalination; Renewable energy; Hydrogen storage

1. Introduction

This paper sets to investigate the technical and financial viability of renewable energy to power reverse osmosis (RO) desalination plants to provide water for the personal use of 50,000 people.

This paper provides details of the following:

- Locations to site desalination plant.
- The RO plant design.
- The modelling process.
- The CAPEX, OPEX and external costs modelled.

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- Results.
- Potential scenario improvements.
- Conclusions.

This paper is based on my PhD Research with The Open University. The degree was awarded in September 2012.

2. Locations for desalination

Millions of people have died in the twentieth century due to severe drought and famines. One of the worst hit areas has been the Sahel region of Africa, which covers parts of Eritrea, Ethiopia and the Sudan. Of these nations, Eritrea has been selected as a site at which to model renewable powered desalination due to its susceptibility to droughts, and consequential loss of life. Eritrea has a substantial coastline, and the sea level rise expected due to climate change has the potential to hasten the intrusion of saline water into the fresh groundwater aquifers in the coastal zone. The focus of this research will be Massawa, which is in a particularly dry part of Eritrea.

Water supply using desalination at Newhaven in South East England will also be investigated, as this is a particularly dry part of the United Kingdom.

3. The RO plant design

RO is a form of filtration, in which the filter is a semi-permeable membrane that allows water to pass through, but not salt.

As freshwater passes through the membrane, the remaining saltwater becomes more concentrated and, for the process to continue, this concentrate, known as the brine, must be continuously replaced by new feed water. To achieve this, the feed water is pumped across the membrane as well as through it; hence, RO is a cross-flow filtration process as depicted in Fig. 1 below.

To model the basic RO plant, it was necessary to define the following:

- Operational characteristics of the RO plant
- Feedwater temperatures
- Water required from the RO plant.

3.1. Operational characteristics of the RO plant

The Dow Industries SW30HR-320 membrane was selected from the options considered as it was the most versatile and robust in operation, in that it could be used with both untreated and pre-treated feedwater at a range of recovery ratios. The "recovery ratio" is defined as the ratio of the desalinated water output-volume to the seawater input-volume used to produce it.

3.2. Minimum number of membranes

The methodology used to identify the minimum number of elements and pressure vessels that would be required to meet the operational objective is shown below in Fig. 2.

ROSA 6.2, Dow Industries RO Design Programme which allows their membranes to be modelled in a variety of states, was used to identify the minimum number of membranes that would meet the operational objectives to generate 7,000 m^3/d (291.67 m^3/h). This was based on a simple plant without Brine Stream recovery (BSR) operating continuously 24 h/d.

The four main operating parameters required to define the minimum number of membranes are highlighted in "Operating Parameters" in Fig. 2 below:

- RO plant membrane limitations
- The maximum allowable salinity of product water
- The chemical composition of the feedwater, and
- The expected feedwater temperature.

3.2.1. RO plant membrane limitations

The simplified typical RO membrane operating parameters are shown below in Fig. 3, which indicates the flowrate and pressure limitations. If operated outside of these, the membrane will:

- Suffer mechanical damage due to excessive pressure/brine flowrate ((a) and (b))
- Not produce water due to inadequate brine flow (c) or
- Produce water with an unacceptable salt concentration (d).

3.2.2. Water salinity

There was a need to ensure that the salinity concentration of the product water did not exceed the acceptable limit.

The allowable salt content was investigated based on the WHO guidance [1] on sodium and chloride. Chloride concentrations in excess of 250 mg/l are likely to be detected by taste, and no health-based guideline value is proposed for chloride in drinking water.

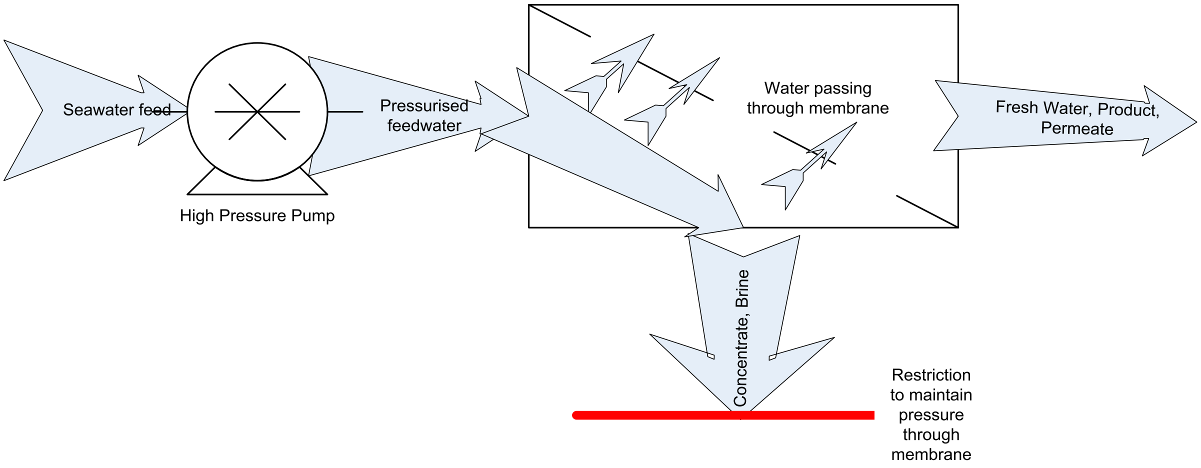
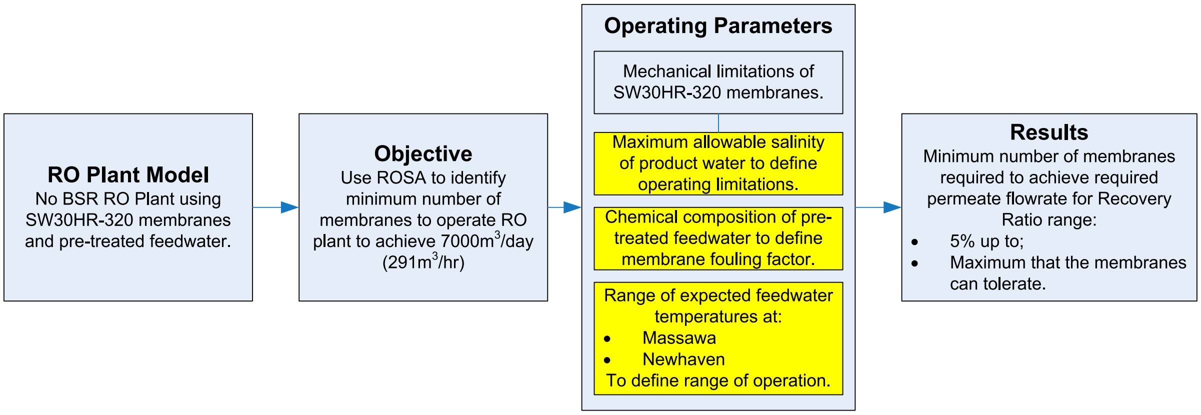


Fig. 1. RO filtration process.



RO Plant Model
No BSR RO Plant using SW30HR-320 membranes and pre-treated feedwater.

Objective
Use ROSA to identify minimum number of membranes to operate RO plant to achieve 7000m^3/day (291m^3/hr)

Operating Parameters
Mechanical limitations of SW30HR-320 membranes.
Maximum allowable salinity of product water to define operating limitations.
Chemical composition of pre-treated feedwater to define membrane fouling factor.
Range of expected feedwater temperatures at:
- Massawa
- Newhaven

To define range of operation.

Results
Minimum number of membranes required to achieve required permeate flowrate for Recovery Ratio range:
- 5% up to;
- Maximum that the membranes can tolerate.

Fig. 2. Methodology to identify minimum number of membranes that the No BSR RO plant requires.

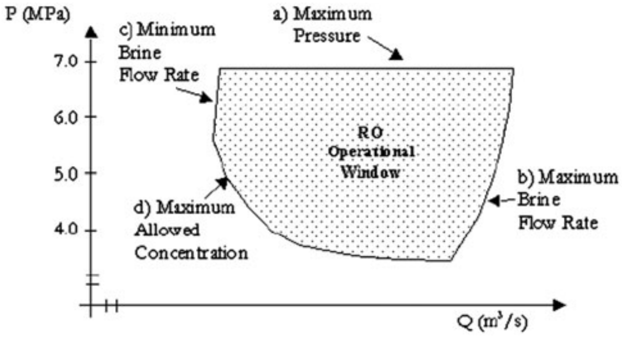


Fig. 3. Typical RO plant membrane operating window.

At room temperature, the average taste threshold for sodium is about 200 mg/l. Again, no health-based guideline value has been derived.

In summary, there is no health-related threshold for salt in drinking water, and the only threshold advised is based on taste. It was concluded that a threshold of 200 mg/l of salt (chloride and sodium combined) would be employed as the salinity limitation for the output from the RO plants.

3.2.3. *Feedwater chemical composition*

The seawater chemical composition used within ROSA was based on both the Newhaven and Massawa feedwater having undergone pre-treatment as defined within Batteryless Photovoltaic RO desalination system [2], and the modelling within ROSA was conducted with a "membrane fouling factor" of 85%.

3.2.4. *Seawater temperatures*

As the RO plant feedwater temperature increases, the permeate flow will increase for a given power level, but at the same time the salt passage will also increase.

The average feedwater temperature was calculated for each hour of the day for one year at each site.

For Massawa, the temperature profile for the Red Sea was taken directly from the thesis by A Murray Thomson[3], as shown in Fig. 4 below.

The equation associated with the curve shown in Fig. 4 above is:

$$\text{Massawa seawater temperature} = 25 + 8\ \sin(2\pi(\text{day of year} - 118)/365))$$

The data for Newhaven were based on the UK Government's Cefas station 20 information from Eastbourne [4], which is 10 miles (16 km) away from Newhaven, and the data were approximated to a polynomial curve, shown below in Fig. 5.

The relationship between seawater temperature (T) and day (x) of the year is given by:

$$T = 0.000000000034^{*}x^{5} - 0.000000015^{*}x^{4} - 0.0000024x^{3} + 0.0014^{*}x^{2} - 0.06^{*}x + 6.2$$

3.2.5. Identification of the minimum number of membranes required

An iterative process, shown below in Fig. 6, was employed to identify the minimum number of membranes required.

This exercise was undertaken through the membrane's range of recovery ratios (from 5% to maximum limit, in 1% stages). The minimum number of membranes was identified for each recovery ratio by either:

- Reducing the numbers of membranes in steps until the plant configuration failed a mechanical limitation, and then noting the number of membranes set in the ROSA run immediately before the failure or
- Increasing the number of membranes in steps until the plant configuration did not fail any of its mechanical limitations.

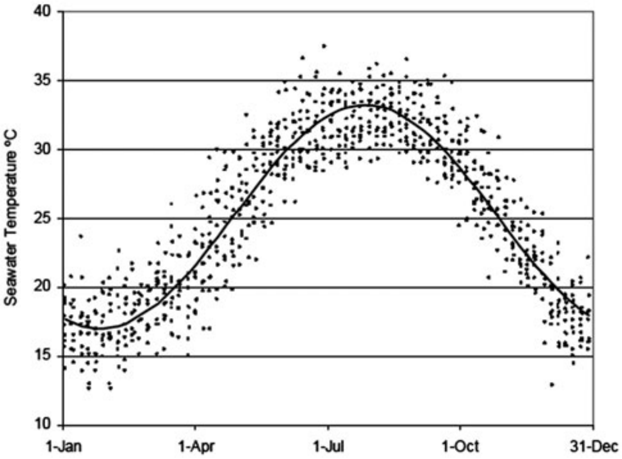


Fig. 4. Red Sea water temperature with fitted sine curve.

3.2.6. Results

The initial results from this exercise (shown below in Fig. 5 below) gave the minimum number of membranes required to produce 7,000 m^3/d, if the plant was run for 24 hours continuously at each recovery ratio.

Fig. 7 below shows that the minimum number of membranes required to produce the required amount of water, within the mechanical limitations of the membrane, varies with the recovery ratio. So it was decided that the RO plant would operate where the minimum number of membranes required was relatively consistent between 15 and 25% recovery ratios, as shown below in Fig. 7.

3.2.7. RO plant design adopted

The plant design adopted for this paper was slightly simplified, and employed a set number of membranes (142 pairs), based on the output from ROSA. It operates between recovery ratios of:

- 15%, below which the minimum number of membranes required increased dramatically, and
- 24 and 25%, at Massawa and Newhaven, respectively, where the brine flowrate reduced to the minimum acceptable level.

The RO plant operating profile is shown below in Fig. 8, in relation to the water production at varying recovery ratios. This design was used as the generic model for both the Newhaven and Massawa sites.

The optimum operating profile across the range of recovery ratios modelled (shown below in Fig. 8) is in keeping with the proposed optimum operating profile within the normal membrane operational window, shown below in Fig. 9.

3.3. Movement of feedwater

In addition to pressurisation power requirements, there is a need to move feedwater from the intake, in

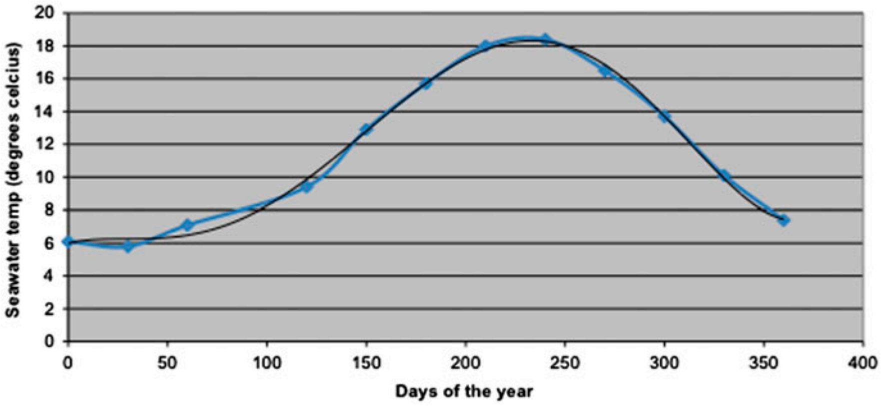


Fig. 5. Seawater temperature curve for Eastbourne.

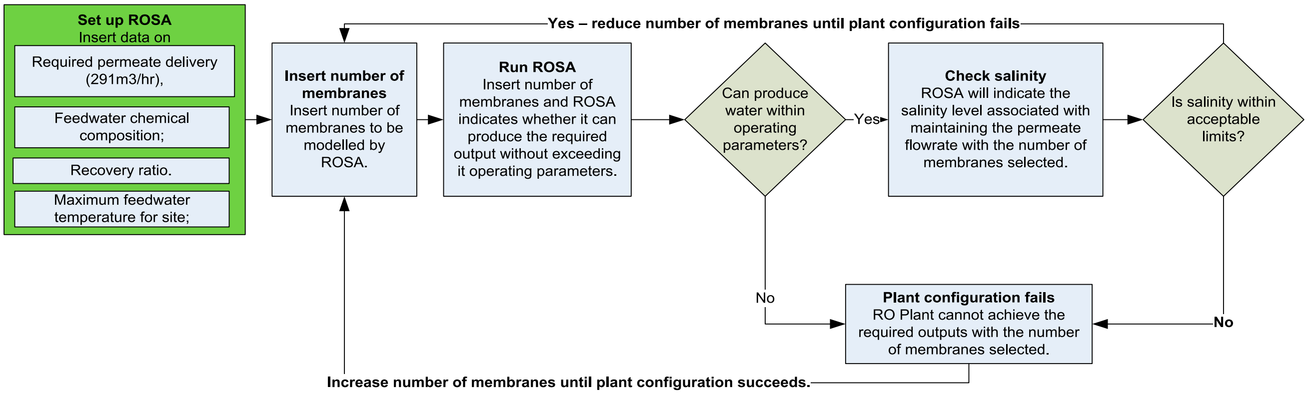


Fig. 6. Identifying the minimum number of membranes.

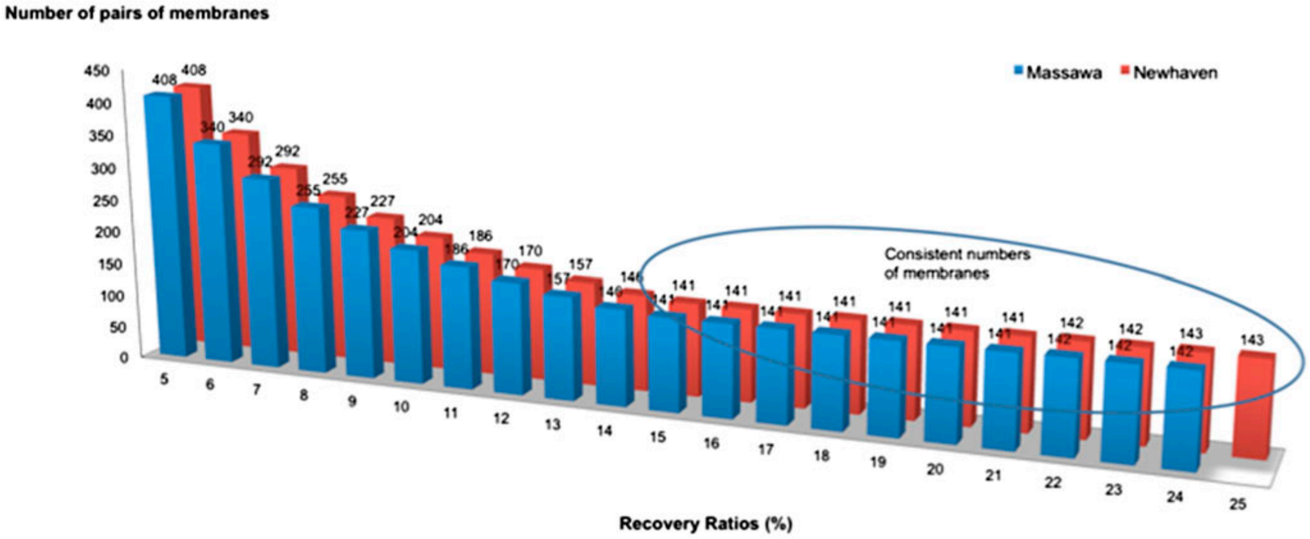


Fig. 7. Minimum number of pairs of membranes at each site for maximum temperature at various recovery ratios.

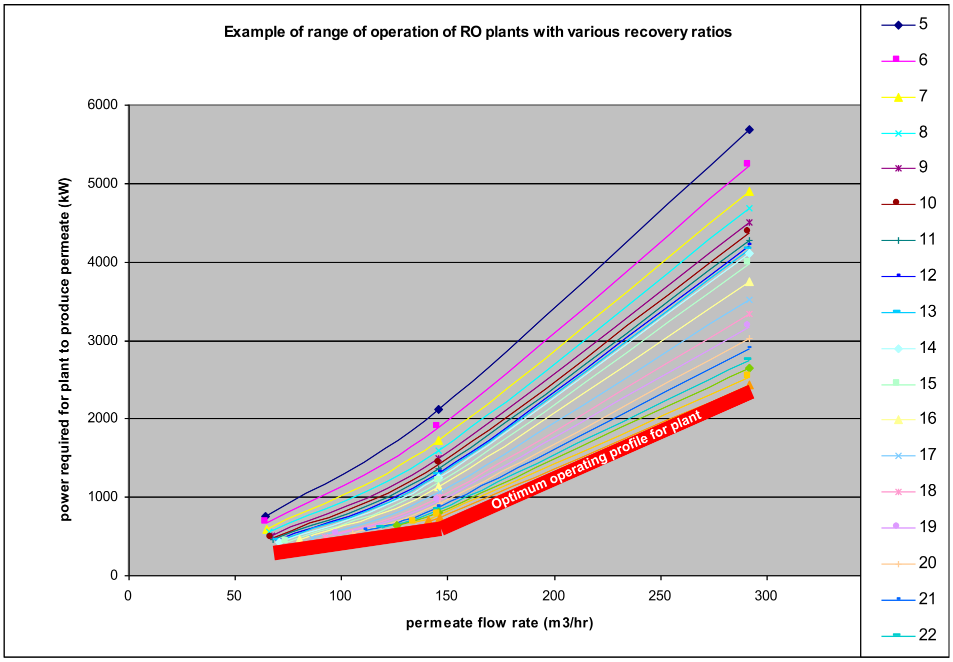


Fig. 8. Optimum No BSR plant operating profile.

preparation for pressurisation. This was modelled based on using seawater Borehole Pumps, which take water from static to around 0.3 bar as suction for HP Pump.

To achieve the various flowrates of feedwater delivery and membrane pressurisation due to expected variations in available power, there is a need to vary flowrate. The working assumption was that the pump and motor system act at 80% efficiency across their full working range.

This constant efficiency is probably unreasonable due to friction, windage losses, design for maximum efficiency at a specific load, etc. An example of expected pump efficiency was found in DOE Tip sheet 2[5], which allowed the relationship between pumping efficiency and the proportion of maximum load to be defined, and applied to refine the estimation of RO plant power consumption across the full range of operating scenarios.

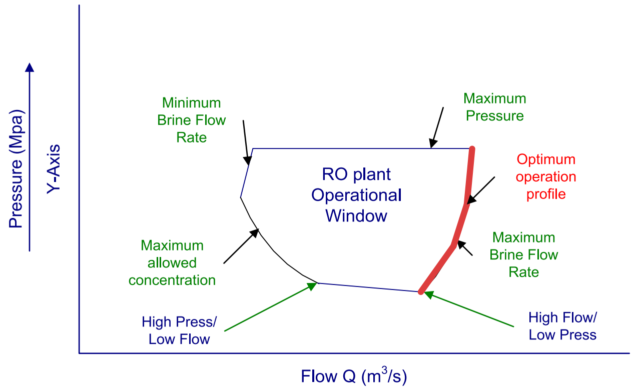


Fig. 9. Optimum operating profile for RO plant from minimum to maximum flow.

3.4. Plant duty

For the purposes of this paper, the plant at both sites provides water for domestic and light industrial (including offices) use. At both locations, it was modeled as running continuously for 12 months of the year, to meet all the domestic and light industrial needs of the town.

It is though noteworthy that the expected duty of a plant of this type in South East England would be to supplement existing established water supplies, and the greatest run duration in a year would be for eight months, nominally March to November.

3.5. Amount of water required

To allow a measure of the effectiveness of the RO plant, a simple relationship of the impacts due to reduced flowrates was developed, and is shown below in Fig. 10.

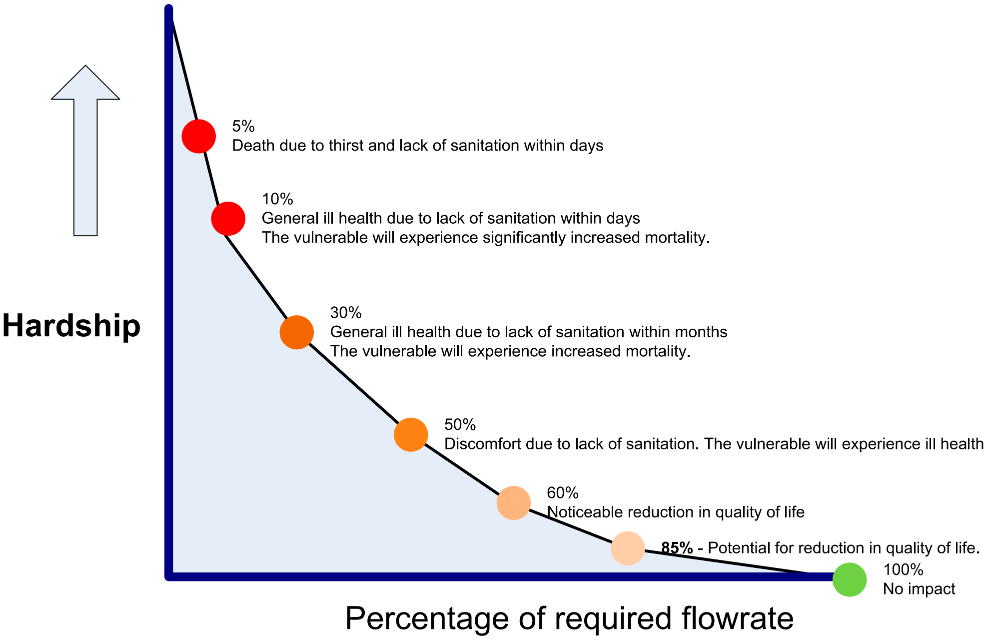


Fig. 10. Impact on human health of varying degrees of water shortage.

Fig. 10 above indicates the impact on human health, expected hardship and required external intervention points at reduced levels of water production from the RO plant, in terms of the proportion of maximum design water delivery. Based on this model, no action would be taken until water production fell below 85% of the full flowrate.

The profiles for water use were based on the usage chart for the rolling hourly water consumption for an individual property in the UK. This daily water use was proportioned for the total water requirement from the RO plant, and for simplicity, no seasonal variations were included. This much-simplified daily water usage cycle is shown below in Fig. 11.

This profile consumes 5,950 m^3 of water over a 24-h period, which equates to 85% of the 7,000 m^3 required daily water production for 50,000 people.This is the minimum water consumption before intervention to manage the lack of water is implemented, and will result in the greatest reservoir size that can reasonably be expected (and should be designed for).

4. The modelling exercise

The modelling exercise was conducted in four main stages using a range of scenarios to simulate varying amounts and types of renewable power being applied to various RO plants as shown below in Fig. 12.

The four stages of modelling development are explained in the following text.

4.1. Stage 1

Stage 1 employed the most reliable renewable resource at each of the sites in question (Solar at Massawa and Tidal Current at Newhaven).

A schematic diagram of the No BSR plant employed for the modelling within this research is shown below in Fig. 13 and an overview diagram of the water and energy processes modelled is shown in the following diagram, Fig. 14.

The No BSR RO plant water production profile at varying input power and feedwater temperatures, derived using ROSA, is shown below in Fig. 15.

This profile was then manipulated using polynomial approximations (as explained in the following section), so that it could be interrogated for any combination of feedwater temperature and power available, to calculate the amount of water delivered.

The methodology employed to calculate the amount of water produced involved taking the data for "power available" vs. feedwater temperature for each individual water delivery setting from minimum (75 m^3/h) to maximum (291 m^3/h), and deriving the corresponding polynomial equations for each of the 14 discrete water delivery curves, as shown below in Fig. 16.

From this set of polynomials, the feedwater temperatures were split further from 3°C intervals to 0.01°C intervals. This ultimately resulted in 3,901 sets

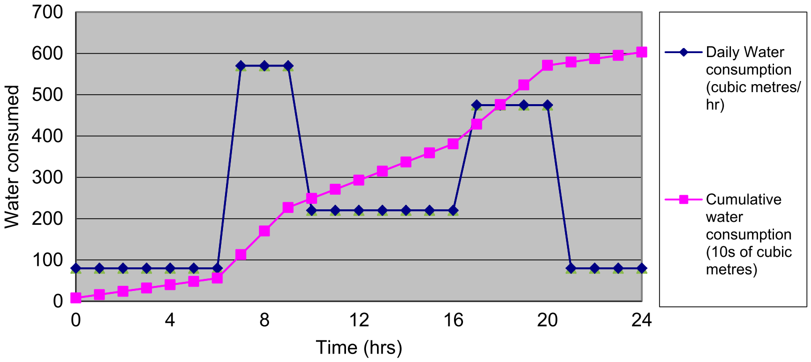


Fig. 11. Daily water usage cycle.

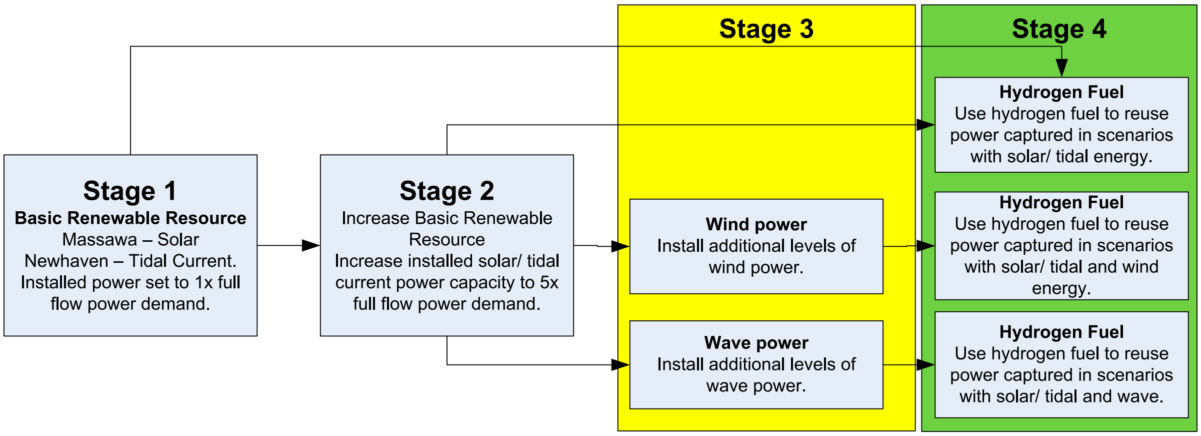


Fig. 12. Four stages of the modelling exercise.

of quadratic polynomials, each relating to a 0.01℃ step in feedwater temperature, representing the amount of water produced from the power delivered, at that feedwater temperature.

The method used to calculate the amount of water generated was a "for" loop in Matlab, as shown below:

```
for i = 1:rwr
    newwater1(i) = polyval(ppolycoef(index(i)),Pg1
    (i));
end
```

where:

Pg1 = the power available to operate the RO plant at each hour during the year. index(i) identifies the location of the prevailing seawater temperature for each hour of the year.

ppolycoeff is a file that contains all the polynomial equations relating to each 0.01℃ step from 3 to 42℃.

i = 1:rwr defines the number of times that the calculation should be conducted before stopping.

i = the number of the calculation being conducted, in this case, conducted in sequence from 1—(rwr) the max number which is 8,760 (the number of hours in a year).

Polyval is the matlab function that then evaluates the polynomial equation identified by (index(i)) making the corresponding Pg at (i) the subject.

Sufficient power was installed at each site so that the maximum power output during the year from the renewable power source would achieve the maximum flowrate of the RO plant. Additional power was then added in discrete levels, up to (and including), the power required to achieve five times maximum flowrate of the RO plant.

4.1.1. Modelling of solar power

HOMER (energy modelling software for renewable energy systems) was employed to derive the solar irradiance on an hour-by-hour basis at Massawa based on the monthly averages shown below in Table 1.

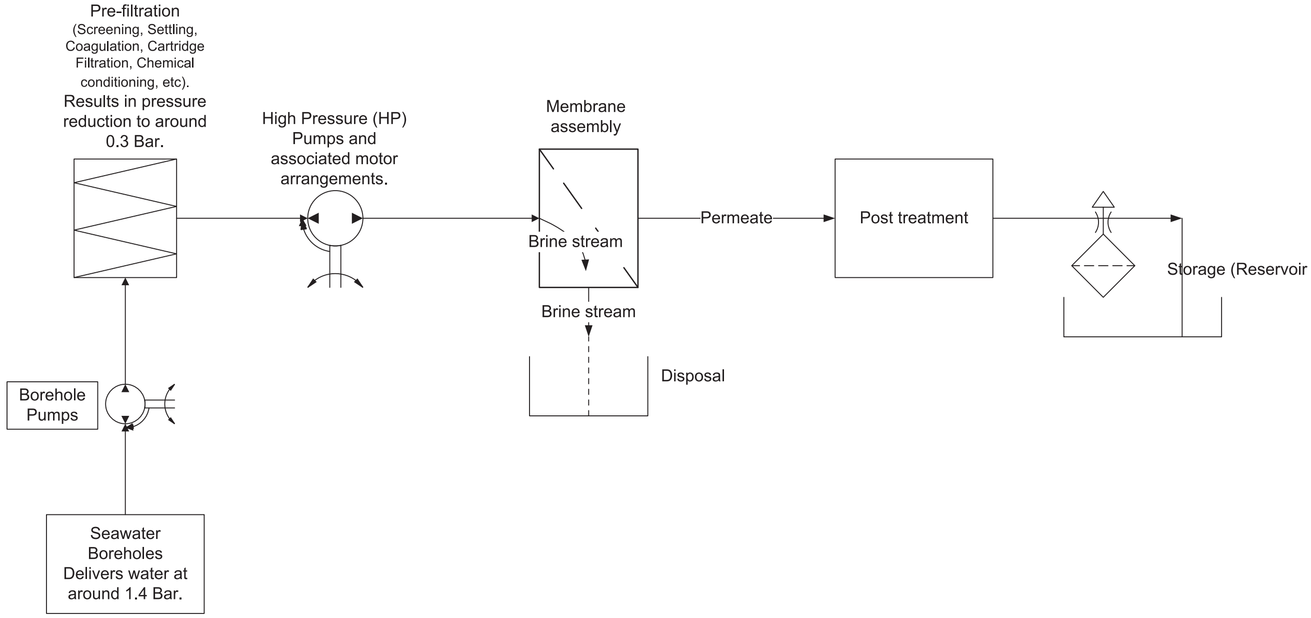


Fig. 13. No BSR plant type used within modelling.

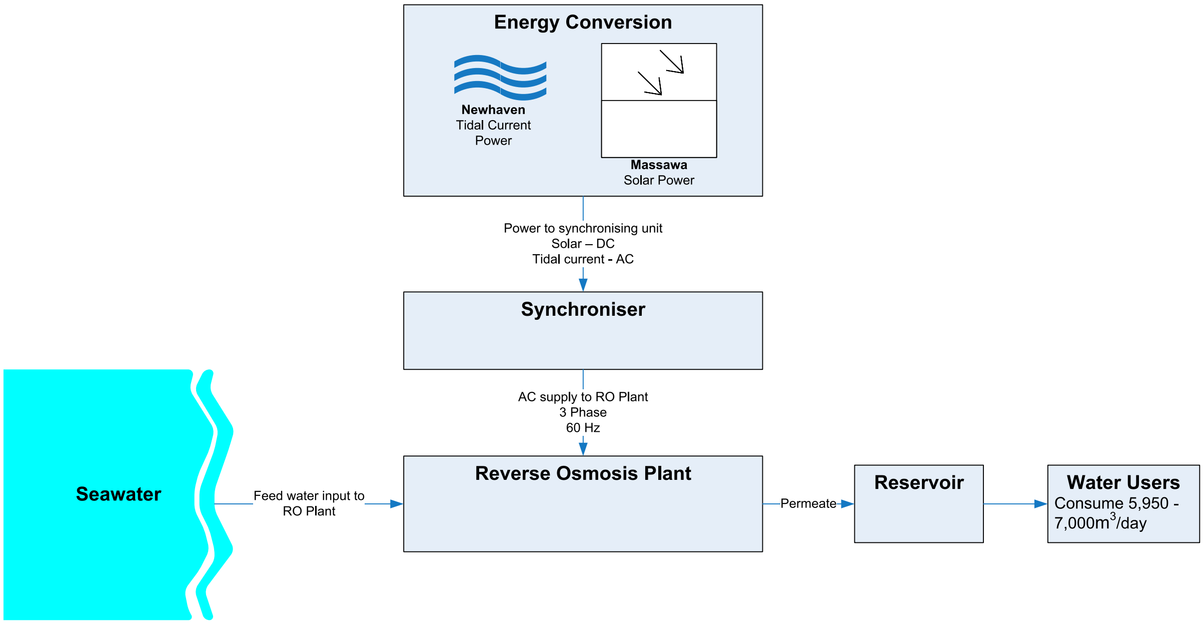


Fig. 14. Single source of renewable energy to power RO plant at both sites.

Table 1 below shows the original data from M. Thomson’s Doctoral Thesis [6] which was converted, and when inputted to HOMER generated the:

- Appropriate “clearness index” to be applied, and;
- An hour- by- hour irradiance profile in terms of W/m^2 which is shown below at Fig. 17.

As can be seen from Fig. 17 above, the maximum irradiance during the year was 4.979 W/m^2.

The photo- voltaic panels modelled were based on Sharp 235 W Solar Panel, Monocrystalline, Clear, NU-U235F1 [7] which is rated at 235 W (Measured at standard test conditions: 25°C, 1 kW/m^2 insolation, AM 1.5) from a panel of 994 mm × 1640 mm. This panel is quoted as 14.4% efficient, but for the purpose of this

Table 1
Average monthly irradiance

Month	Original monthly average ($W/m^2/d$ during that day)	Conversion to kW/h	Clearness index* applied by HOMER
Jan	303	7.272	0.895
Feb	357	8.568	0.954
Mar	366	8.784	0.884
Apr	376	9.024	0.855
May	337	8.088	0.754
Jun	306	7.344	0.686
Jul	300	7.2	0.674
Aug	301	7.224	0.684
Sep	330	7.92	0.784
Oct	319	7.656	0.830
Nov	308	7.392	0.891
Dec	295	7.08	0.905

*The "clearness index" is a dimensionless number between 0 and 1 indicating the fraction of the solar radiation at the top of the atmosphere that is able to pass through the atmosphere to the Earth's surface.

model is only credited with 10% efficiency to account for power conversion and ambient temperature losses.

4.1.2. Modelling of tidal current power

From the multitude of tidal device options available, the SeaGen Turbine device was selected for use in this research and is shown below in Fig. 18.

4.1.2.1. Model of SeaGen operation

The SeaGen Turbine's power output in relation to the prevailing tidal current speed was approximated using a fifth- order polynomial which is shown on the graph in Fig. 19 below.

It is noteworthy (as can be seen in Fig. 19 below) that due to the limited tidal current speeds at Newhaven, the SeaGen Turbine is (at best) not expected to achieve more than one-third of its rated capacity during the year. This polynomial was applied to the tidal current speeds derived for Newhaven resulting in the power output from a single 1,113 kW over the course of one year, shown below as Fig. 20.

4.2. Stage 2

Stage 2 employed the same methodology as Stage 1 (application of the most reliable power source at each site), but for the BSR RO plants (Pelton Wheel and Pressure Exchanger).

4.2.1. Pelton Wheel

The Pelton Wheel RO plant system modelled is shown below in Fig. 21.

As shown in Fig. 21 above, the Pelton Wheel BSR RO plant design utilises the brine/concentrate stream to power a Pelton Wheel turbine, which is mechanically linked to a high- pressure pump (HP p/p) arrangement. The power produced from the Pelton Wheel is used to partially pressurise the incoming feedwater which reduces the external power required to raise the feedwater to an adequate pressure for desalination via the RO plant membranes. Due to the extraction of energy from the brine stream, the brine must be pumped away for disposal. The resulting Pelton Wheel BSR RO plant water production profile, at varying input power and feedwater temperatures, is shown below in Fig. 22.

4.2.1.1. Calculation. The general equation employed was:

Pelton Wheel BSR RO plant energy
= energy to power simple (no-BSR) plant
− energy recovered by Pelton Wheel
+ energy to remove brine from site.

The energy recovery from the Pelton Wheel is given by:

$$(V_c \times P_c \times \eta_{\mathrm{turb}})/36$$

where:

V_c = volume of concentrate (m^3)
P_c = concentrate pressure (bar)
η_{turb} = efficiency of Pelton Wheel turbine taken here as constant 88% based on operating experience at the Dhekelia seawater desalination plant [8].

4.2.2. Pressure exchanger

The Pressure Exchanger RO plant system modelled is shown below in Fig. 23.

As shown in Fig. 23 above, the Pressure Exchanger BSR RO plant uses the brine/ concentrate stream to pressurise a hydraulic chamber. This hydraulic chamber acts on a piston arrangement which in turn is used to partially pressurise the incoming feedwater. A booster pump then raises the now partially pressurised feedwater to the correct pressure to combine with the feedwater pressurised by the high- pressure pump for desalination by the RO plant membranes.

After pressurising the incoming feedwater, the brine stream (which is still partially pressurised) is discharged using valve arrangements as a low -pressure brine stream.

The resulting Pressure Exchanger BSR RO plant water production profile, at varying input power and feedwater temperatures, is shown below in Fig. 24.

4.2.3. Calculation

The general equation employed was:

$$\begin{aligned}\text{Pressure exchanger BSR RO Plant energy} = {} & \text{Energy to produce permeate for No BSR plant} \\ & - \text{energy recovered by pressure exchanger} \\ & + \text{energy required to boost pressure of concentrate for} \\ & \quad \text{re} - \text{applicationtomembranes.}\end{aligned}$$

4.2.3.1. Booster pump power demand. The booster pump power demand was taken as:

The appropriate proportion of the energy required to boost diverted feedwater to achieve full feed pressure, and the volume of water this boosting acts upon.

This was modelled using the following equation:

$$\begin{aligned}\text{Booster pump power} = {} & \text{Non-BSR pressurisation power for that scenario} \\ & \times ((\text{booster pressure required}/\text{membrane feed pressure}) \\ & \times (\text{volume of feedwater to be boosted}/\text{volume of feed})).\end{aligned}$$

As was the case in Stage 1, additional power was added in discrete levels up to (and including) the power required to achieve five times maximum flowrate of each of the RO plants.

The Solar and Tidal Current power plants were sized as the equivalent of the conventional power plant that would need to be installed to achieve and maintain maximum flowrate for the BSR RO plants.

4.3. Stage 3

There were two aspects to stage 3 as the model attempted to make the scenarios competent:

- Addition of wind power.
- Addition of wave power.

4.3.1. Addition of wind power

4.3.1.1. Newhaven. The wind resource available at Newhaven was taken from the UK wind speed database NOABL [9] and is shown below in Table 2.

4.3.1.2. Massawa. The monthly average data at Massawa were taken from local weather reports on the weather base web site [10], and is presented below in Table 3.

These data were then applied to HOMER to derive the wind speed for each hour of the year which is shown below in Fig. 25.

Wind power was added to the single renewable power source scenarios for No BSR and BSR RO Plants at varying levels in an attempt to allow the RO plant to operate at a high level of water production continuously. This hybridised power source was based on the use of 2,000 kW turbines based on a scaled -up Fuhrlander 250 operating profile obtained from the HOMER library.

Table 2
Average wind speed at Newhaven

Height of reading	Mean average wind speed (m/s)
10	6
25	6.7

Table 3
Average wind speed at Massawa

Data	Wind speed at 10 m height (m/s)
Jan	3.576
Feb	3.576
Mar	5.812
Apr	5.812
May	5.812
Jun	5.812
Jul	4.917
Aug	5.364
Sep	4.917
Oct	5.364
Nov	5.364
Dec	5.364
Annual Average	**5.141**

4.3.2. Addition of wave power

The Wave Dragon was selected for use in this research to convert wave motion to power at each site. It is an "overtopping" wave energy converter and floats slack-moored to allow it to move in the direction of the prevailing waves.

The principle of operation of the wave dragon device is illustrated below, based on Ocean Energy Technologies for Renewable Energy Generation [11], in Fig. 26.

The Wave Dragon works by facing its outstretched collector arms towards the oncoming waves and concentrating the wave front towards the ramp at the front of the structure. This focusing increases the wave height at the ramp, which in turn acts like a beach and causes the waves to overtop the device without breaking (and therefore, without losing their potential energy) into the reservoir behind it. As shown in Fig. 26 below, the water, now stored in the reservoir, at a higher level than the sea, is returned through low-head turbines powering electrical generators producing power.

The power production profiles for Massawa and Newhaven are shown below in Figs. 27 and 28, respectively, with the maximum values achieved during the year at each site.

4.4. Stage 4

Stage 4 was the use of hydrogen storage of captured energy, and reuse with primary energy and hybridised (primary with wind or wave) power scenarios for No BSR and BSR RO Plants. This was to allow the power captured during normal RO plant operation to be reapplied at times when insufficient power was being produced to maintain maximum RO plant water production.

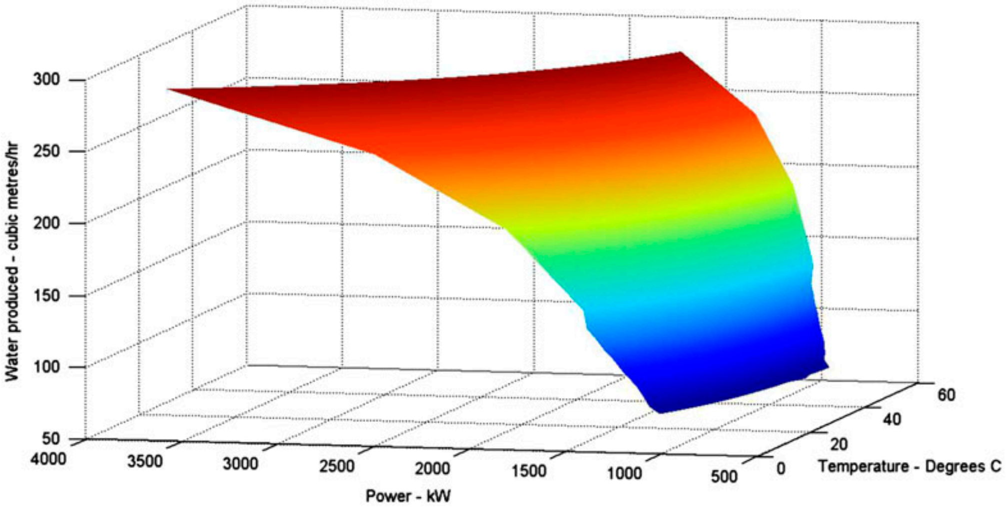


Fig. 15. No BSR RO plant water production profile at varying power and feedwater temperature.

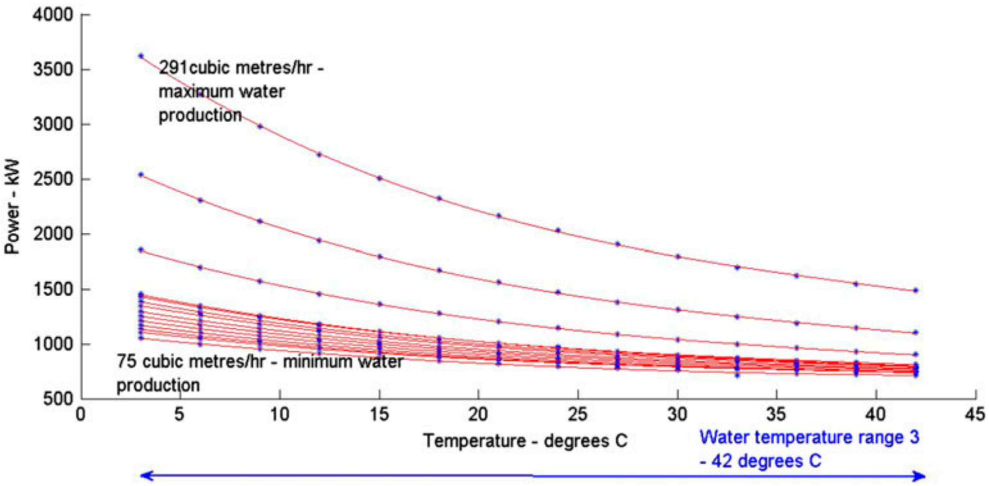


Fig. 16. Approximating curves for various levels of water production from the No BSR RO plant.

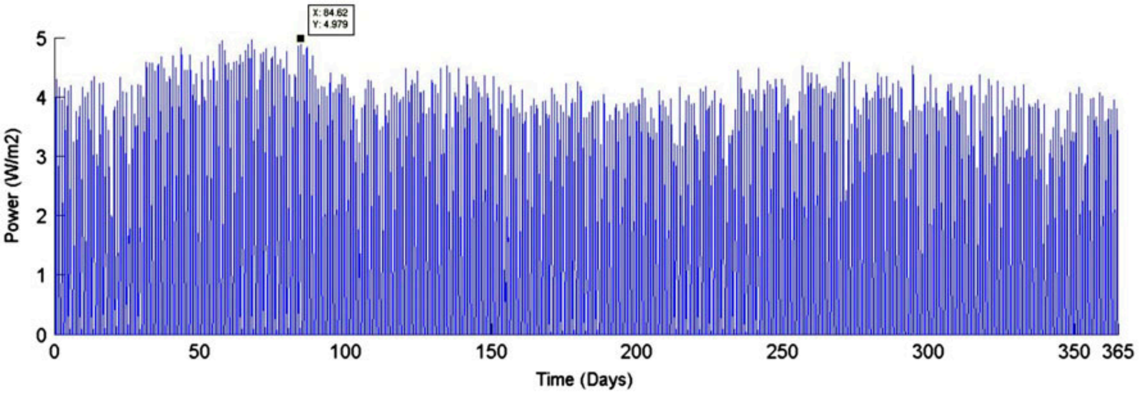


Fig. 17. Hourly irradiance at Massawa over one year.

The water used and lost due to the electrolysis process as part of the hydrogen fuel cycle is considered to be negligible.

The conversion and reuse efficiency of hydrogen was taken as 22% as shown in Fig. 29 below.

4.5. Scenarios modelled

There were 270 scenarios modelled with BSR and No BSR RO plants limited to 7,000 m^3/d output capacity. Each scenario used the following details for each hour of the year:

- The input renewable power.
- The corresponding feedwater temperature.
- The power that could be used by the RO plant i.e. power above minimum and below maximum flowrate thresholds for RO plants with 7,000 m^3/d output capacity.
- The power wasted, i.e. power produced minus power outside RO plant operating thresholds.
- The water produced during that hour, which was calculated in Matlab using the RO plant operating profiles shown in Figs. 15, 22 and 24 for the No BSR, Pelton Wheel BSR and Pressure Exchanger BSR RO plants, respectively.
- The water deficiency/ remaining considering the demands of the local users.

The measure of technical competence of the scenarios was the percentage of the water demand over the course of the year, which the RO plant managed to satisfy. There were some scenarios where the addition of hydrogen fuel at Massawa and Newhaven, enabled the modelled scenarios to achieve maximum outputs, just below 100% of the water required by the local population, but there was limited success in

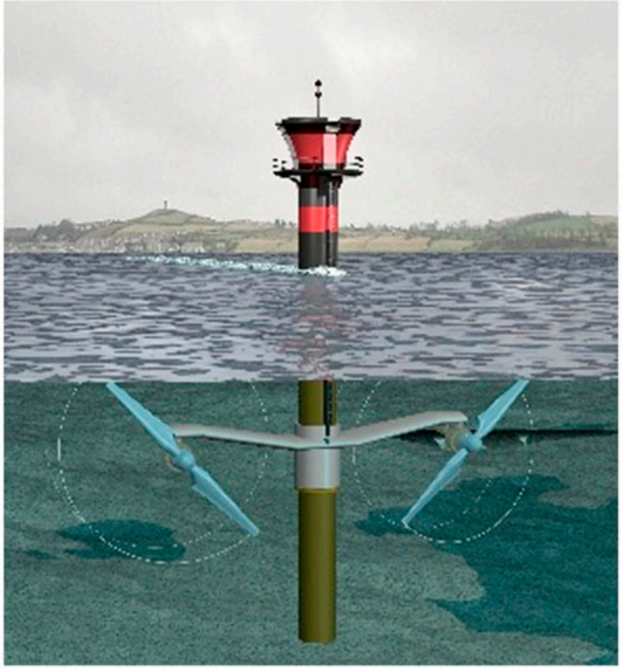


Fig. 18. Marine current turbines limited SeaGen turbine.

identifying technically competent scenarios that were able to meet the water demands of the local population without using hydrogen storage.

4.5.1. Scaling of renewable energy scenarios

It was clear that if the scenarios were scaled-up (extrapolated), competent scenarios could be identified where the full demand of the local water users could be met even without energy storage.

4.5.2. Extrapolations considered

Three extrapolations of the modelling were considered to identify competent scenarios:

(a) Increase the size of the RO plant, and therefore, output capacity of the RO plant to enable the excess power which is normally wasted, when the RO plant is limited to 7,000 m^3/d output capacity, to be used.
(b) Increase the size of power installation to allow the RO plant to run continuously.
(c) Increase RO and Power plant by the ratio of water shortfall, i.e. if RO plant and Power scenario makes 50% of required water, both the RO plant and installed power are doubled in size.

The method adopted was to increase the size of both the RO and installed power plant, in equal proportion, option (c) above, to achieve the required volume of water production.

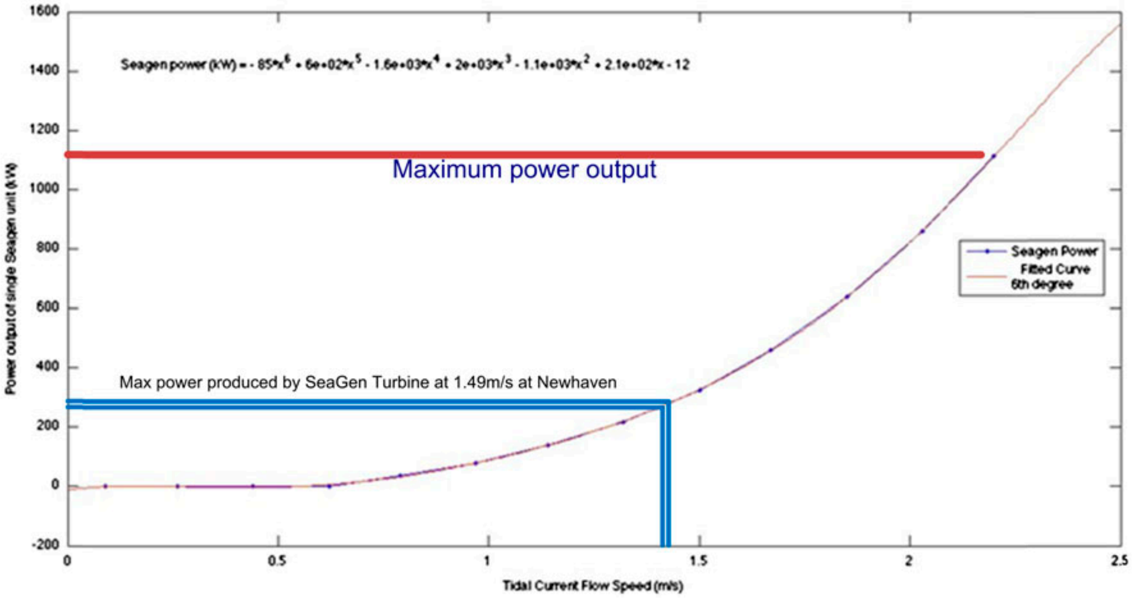


Fig. 19. Power output of single SeaGen turbine.

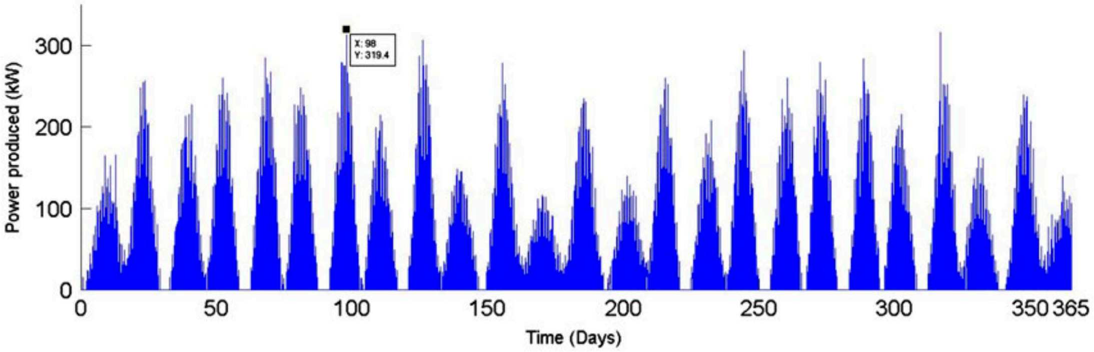


Fig. 20. Power output from single SeaGen turbine at Newhaven over 1 year (kW).

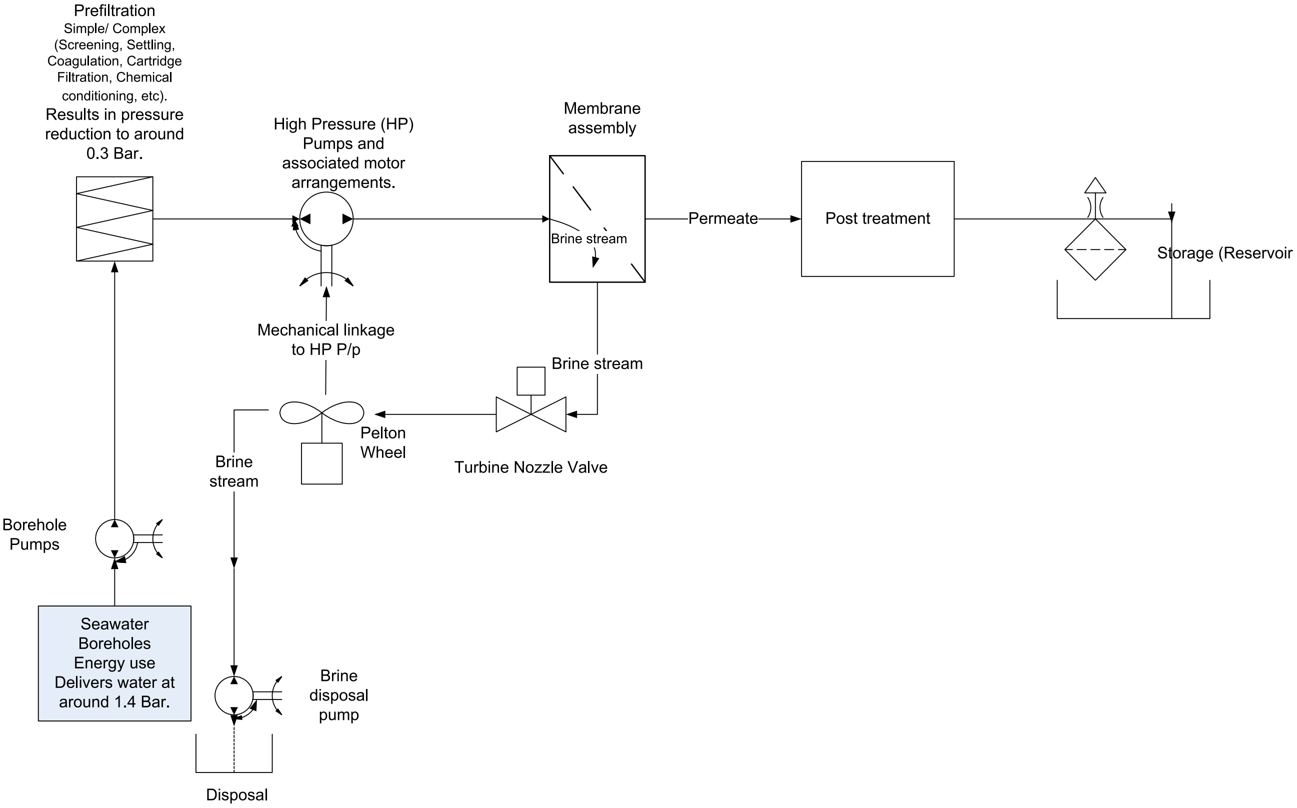


Fig. 21. Simple plant using Pelton Wheel for BSR design.

4.6. Model of non-varying power sources

4.6.1. No BSR

The power demand for the No BSR RO plant (as would be supplied by a non-varying power source) is shown below in Fig. 30.

As shown in Fig. 30 below, Newhaven requires its maximum input of 3,327.74 kW at 23 d and 1 h. For the purposes of this research, the plant size that the renewable energy system was compared with was a conventional plant of 3,400 kW.

Also shown in Fig. 30 below, Massawa requires its maximum input of 2,379 kW at 24 d and 12 h. For the purposes of this research, the plant size that the renewable energy system was compared with was a conventionally plant delivering 2,400 kW.

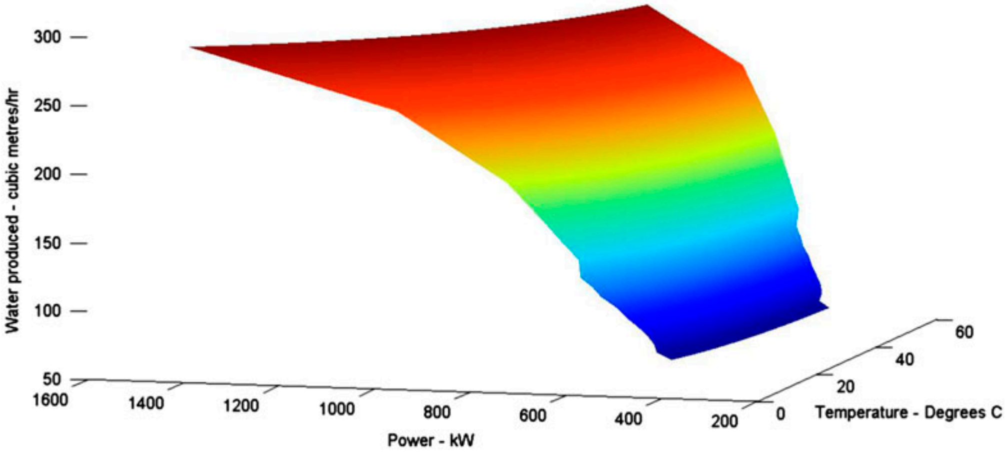


Fig. 22. Pelton Wheel RO plant water production profile at varying power and feedwater temperature.

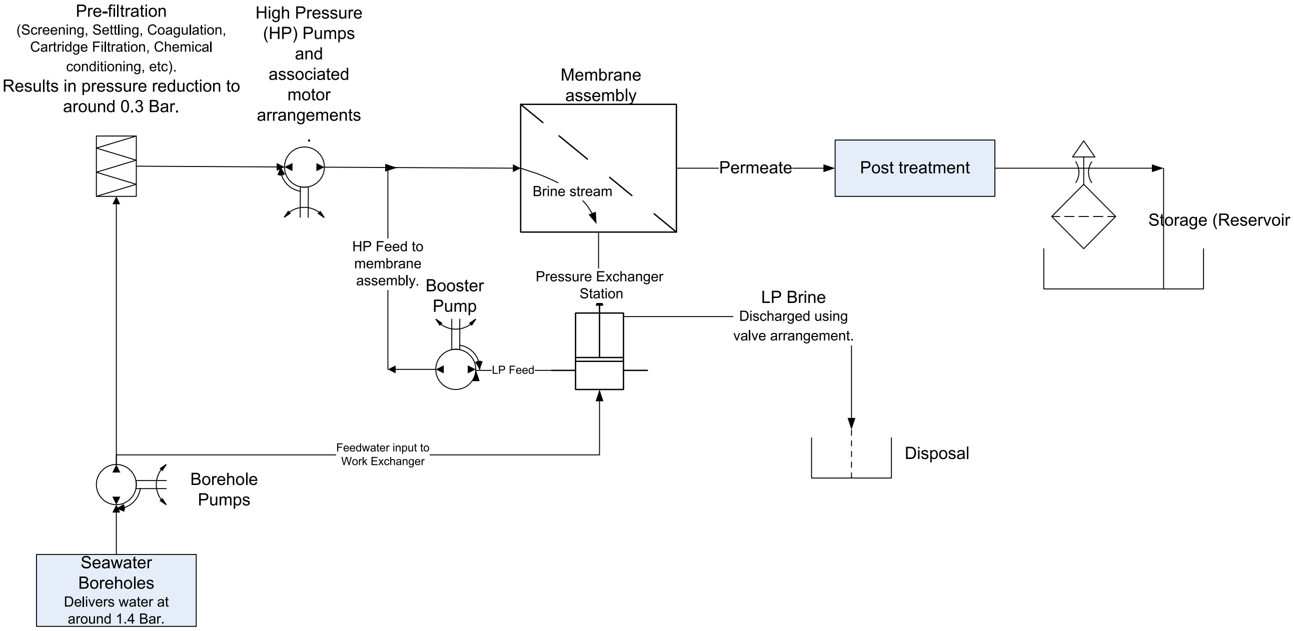


Fig. 23. RO plant using Pressure Exchanger for BSR design.

4.6.2. BSR

The power demand for the BSR RO plants is shown below in Fig. 31.

4.6.2.1. Massawa. As shown in Fig. 31 above, Massawa requires its maximum input of 99 and 772 kW at 24 d for the Pelton Wheel and Pressure Exchanger RO plants, respectively. For the purposes of this research, the plant sizes that the renewable energy was compared with were conventional plants of:

- Pelton Wheel—1,000 kW
- Pressure Exchanger—800 kW.

4.6.2.2. Newhaven. Also shown in Fig. 31 above, Newhaven requires its maximum input of 1,310 and 1,062 kW at 21 and 22 d for the Pelton Wheel and Pressure Exchanger RO plants, respectively. For the purposes of this research, the plant sizes that the renewable energy was compared with were conventional plants of:

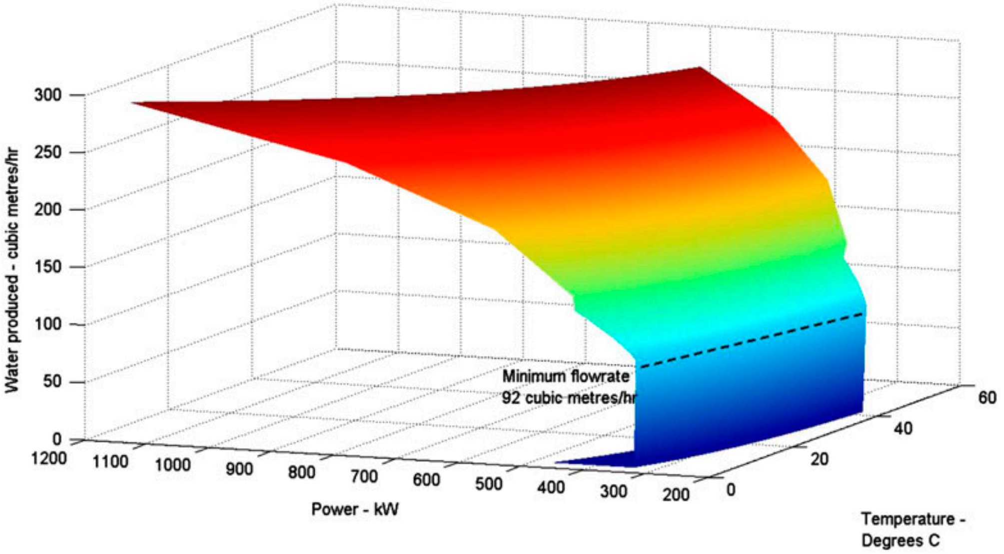


Fig. 24. Pressure Exchanger RO plant water production profile at varying power and feedwater temperature.

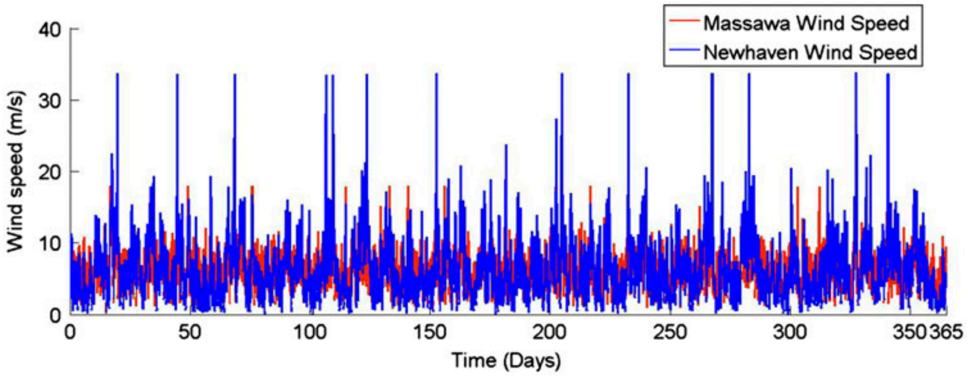


Fig. 25. Wind speeds at Massawa and Newhaven over 1 year.

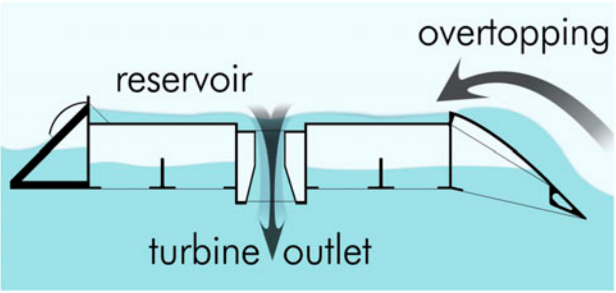


Fig. 26. The principle of the Wave Dragon technology.

- Pelton Wheel—1,400 kW
- Pressure Exchanger—1,100 kW.

5. Costs

This section identifies the indicative costs that were used within the modelling to compare the costs of the renewable powered scenarios with conventionally powered scenarios.

The first part of the section deals with CAPEX and OPEX costs and the later part of this section identifies the external costs associated with the conventionally powered scenarios.

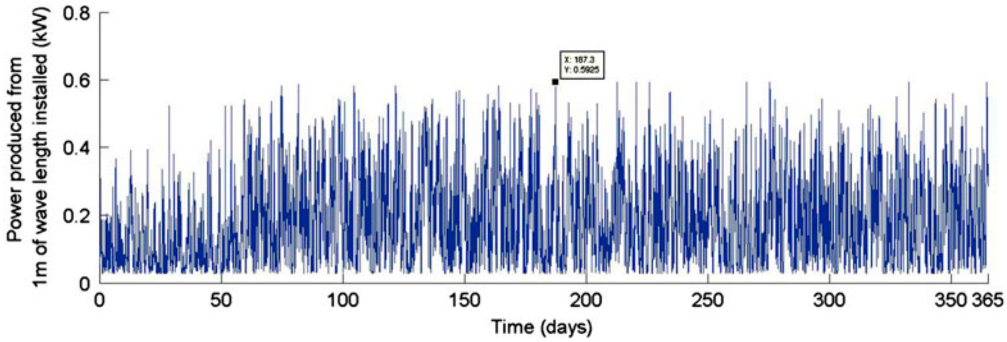


Fig. 27. Power produced by 1 m of Wave Dragon at Massawa during 1 year.

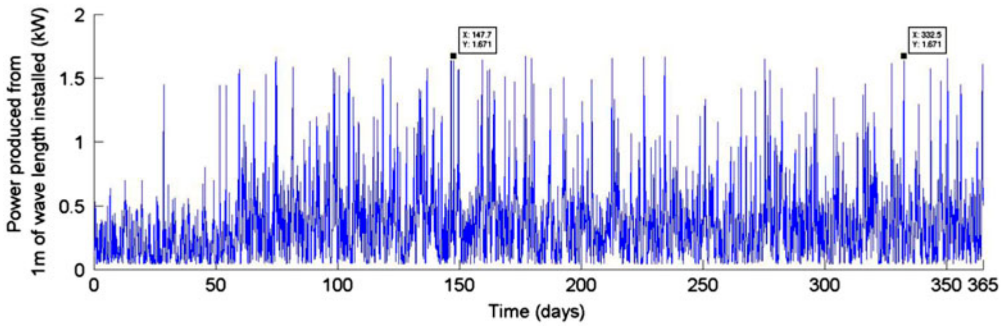


Fig. 28. Power produced by 1 m of Wave Dragon at Newhaven during 1 year.

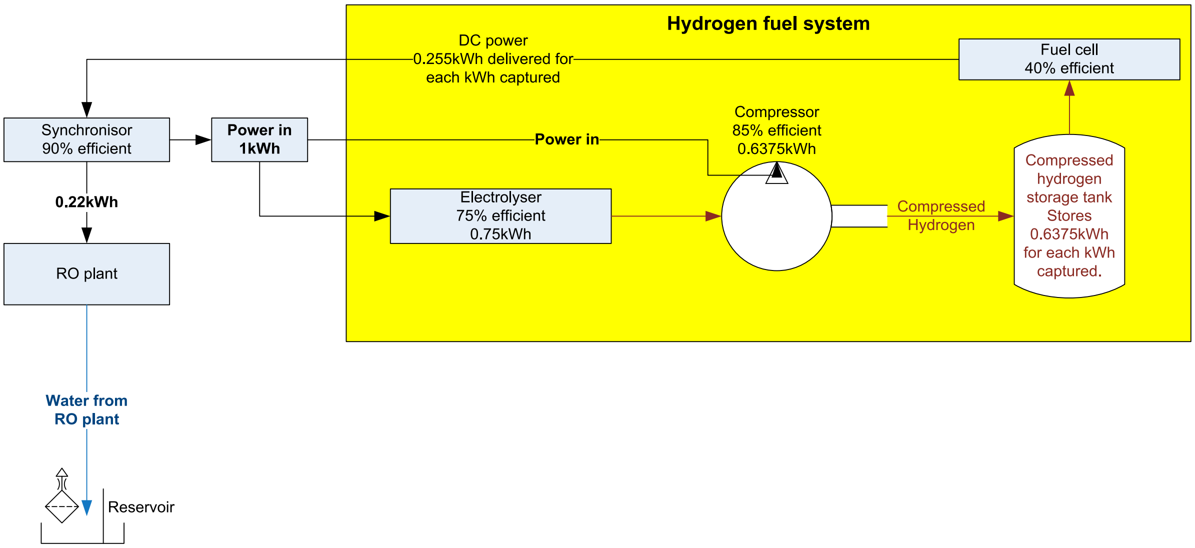


Fig. 29. Efficiency of hydrogen fuel system components.

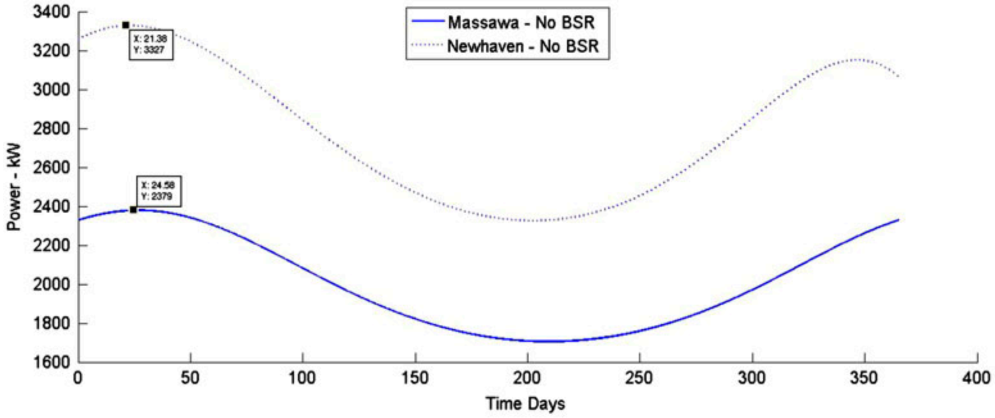


Fig. 30. No BSR power profile over 1 year to maintain maximum flowrate at Massawa and Newhaven.

5.1. CAPEX and OPEX costs

5.1.1. RO plant costs

Table 4 below shows the CAPEX and OPEX costs associated with the unscaled RO plants employed at each site based on various sources.[1]

Table 4
Capital, O&M and total costs over 25 years for RO plants

	No BSR	Pelton Wheel	Pressure Exchanger
Capital costs (£ ×10^6)	9.27	10.38	11.12
O&M costs (£ ×10^6/ annum)	0.31		
Total costs over 25 years (£ ×10^6)	48.8	79.1	56.0

5.1.2. Reservoir cost

The reservoir was priced as holding 15% of the annual production of a plant that produces 100% of the annual water required (2,555,000 m^3). 15% is taken as 383,250 m^3 at the end of the year. This equates to a reservoir costing £82,115,200 based on extrapolation of various reservoir costs presented in "Design, Construction and repair of potable water reservoirs" [12]

5.1.3. Renewables

Table 5 below shows the CAPEX and OPEX costs associated with the renewable energy sources employed at each site.

5.1.4. Hydrogen fuel system

Table 6 below shows the CAPEX and OPEX costs associated with the hydrogen production, storage and reuse system modelled.

5.1.5. Conventional power costs

The conventional power sources that were modelled as the options that the renewable energy sources needed to demonstrate viability against are as follows:

- Massawa—Local diesel generators
- Newhaven—Centralised coal- fired plant with carbon capture and storage (CCS) facilities.

Table 7 below shows the CAPEX and OPEX costs associated with the conventional power plants

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[1] Affordable Desalination (ADC)—see http://www.affordabledesal.com/home/test_data.html on 14 January 2011 for an RO plant using the Filmtec SW30HR-380 membrane; Discussions with Daniel Shackleton—Director of Salt Separation Limited, on 9 November 2009. See website at http://www.saltsep.co.uk/ for greater details of Salt Separation Limited. Discussion with William J. Conlon, P.E., BCEE, F.ASCE Technical Manager, Principal Professional Associate. Water Technical Excellence Center, Parsons Brinkerhoff Americas, Inc; Discussion with Philip Boswell (International Technical Consultant) Accepta. See website at http://www.accepta.com/ for details of Accepta; Desalination in Florida: Technology, Implementation, and Environmental Issues. Division of Water Resource Management, Florida Department of Environmental Protection. (April, 2010). Available at http://www.dep.state.fl.us/water/docs/desalination-in-florida-report.pdf

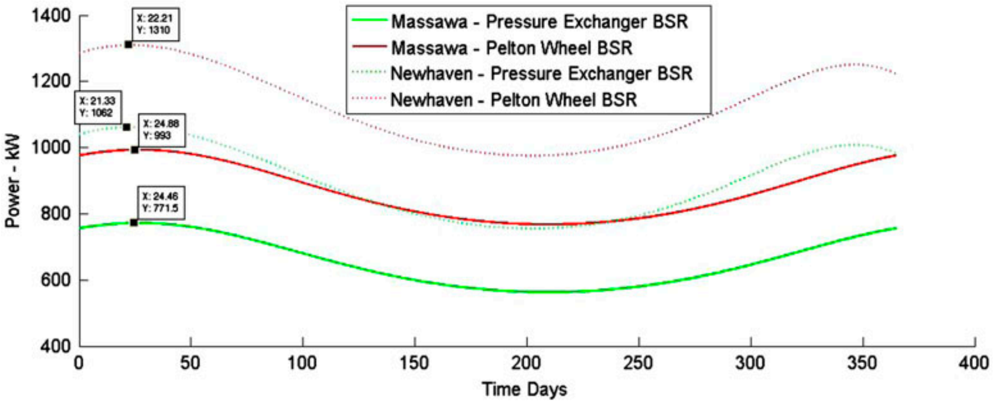

Fig. 31. BSR RO plant power profiles over 1 year to maintain maximum flowrate at Massawa and Newhaven.

modelled at each site, which were based on various sources[2].

5.1.6. Externalities of energy production and use

The hidden costs, (the externalities), borne by society for the use of conventional fuels are not reflected the CAPEX and OPEX figures above.

The best available studies of externalities of power generation are the European Union's "ExternE Project" [21], and its successor, "New Energy Externalities Development for Sustainability (NEEDS)".

Table 5
Capital and O&M costs of renewable energy sources

	Solar [13]	Tidal current [14]	Wind [15]	Wave [16]
Capital costs (£/kW installed)	3,000	1,288	1,200	4,000
O&M costs (£/kW/annum)	15	51	37	27

Table 6
Capital and O&M for hydrogen fuel system

	Electrolyser [17]	Hydrogen storage [18]	Fuel cells
Capital costs (£/kW installed)	1,320	30.15	3,500 [19]
O&M costs (£/kW/annum)	26*	2.43*	45 [20]

*A standing cost of 2% of the CAPEX costs was taken as the annual O&M cost.

5.1.7. Externalities associated with coal- fired plant with CCS technology to be employed in Newhaven

ExternE presents external costs for the use of coal and lignite in the UK of 4–7 € cent/kWh. For the purposes of this research, the external cost associated with electricity generation via coal at Newhaven was taken as the lower end of the range 3.4 p/kWh.

The conventional power plant used at Newhaven is modelled as having CCS, which is taken as being 90% efficient at removing carbon dioxide.

The final ExternE report provides a breakdown of the externalities of electricity production using coal in Germany, which is attributed with external costs for

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[2] These sources include: Massawa–Cost of diesel generators —Discussion with Mie Gabriel—Sales Manager Power Electrics (Bristol) Ltd see http://www.power-electrics.co.uk/ for greater detail of power electrics organisation; Data Preview—January 2011—International Fuel Prices 2010/2011 by The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Available at http://www.gtz.de/de/dokumente/giz2011-international-fuel-prices-2010-2011-data-preview.pdf. Newhaven–F.E.E. Mattei, A. Markandya. CASES (Cost Assessment of Sustainable Energy Systems). Deliverable no. D.4.1 "Private costs of electricity and heat generation". (August 2008). Available at http://www.feem-project.net/cases/documents/deliverables/D_06_1%20part2%2008_09.pdf; The Federal Institute for Geosciences and Natural Resources (Bundesanstalt fur Geowissensschaften und Rohstoffe - BGR) Reserves, Resources, Availability TableSENERGY RESOURCES 2009 Table A 5–1: Hard Coal in 2007: Production, Reserves, Resources and Remaining Potential [in Mt] available at http://www.bgr.bund.de/EN/Themen/Energie/Downloads/Energierohstoffe_2009_Tabellen_en.pdf?__blob=publicationFile&v=2; C. Bauer, T. Heck, R. Dones (PSI), O. Mayer-Spohn, M. Blesl. Final report on technical data, costs, and life cycle inventories of advanced fossil power generation systems. (March 2008) New Energy Externalities Developments for Sustainability (NEEDS) INTEGRATED PROJECT. Priority 6.1: Sustainable Energy Systems and, more specifically, Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy. Deliverable no. 7.2 - RS 1a. Available at http://www.needs-project.org/docs/RS1a%20D7.2%20Final%20report%20on%20advanced%20fossil%20power%20plants.pdf

Table 7
Capital and O&M conventional power plants

	Massawa—diesel generator costs for 25 years				Newhaven—coal fired plant with CCS for 25 years			
	Installed power costs (£)	Fixed O&M costs (£)	Fuel costs (£ $\times 10^6$)	Total scenario costs (including RO plant and reservoir) (£ $\times 10^6$)	Installed power costs (£ $\times 10^6$)	Fixed O&M costs (£ $\times 10^6$)	Fuel costs (£ $\times 10^6$)	Total Scenario costs (including RO plant and reservoir) (£ $\times 10^6$)
No BSR	380,000	40,000	100.2	**232**	9.5	4.6	66.7	**212**
Pelton Wheel	160,000	27,500	43.4	**205**	3.9	1.9	27.0	**194**
Pressure Exchanger	125,000	22,500	32.8	**171**	3.1	1.5	21.4	**164**

the use of coal and lignite of 3–6€ cent/kWh. For the purposes of this research, the breakdown of externalities presented for Germany is taken as reasonable to apply to the UK in spite of the fact that Germany is generally accepted as having more efficient coal- fired power stations as stated in Cleaner Coal [22] below:

> "All UK coal-fired power stations use … combustion processes with efficiencies of ~36–39%" in comparison to the fact that "Supercritical plants operating in Denmark and Germany reach efficiencies of 47%".

Of the external costs in Germany, those attributed to the avoidance of CO_2 produced, based on an avoidance cost of 19 Euro/ton of CO_2, are 63% of the total external costs for producing electricity using coal. So, to take account of the coal- fired plant with CCS available to Newhaven, the external cost is reduced to take account of the CCS's efficiency (taken as 90%) at capturing CO_2. So, the cost due to externalities to power the RO plants at Newhaven is 1.47 p/kWh based on:

$$\begin{aligned}\text{Cost due to externalities} &\\ &= 3.4\text{p (total cost of coal externalities)}\\ &\quad - (\text{benefit of } CO_2 \text{ capture}).\end{aligned}$$

$$\begin{aligned}\text{The benefit of } CO_2 \text{ capture} &= 0.63\,(\text{portion of externalities associated with carbon dioxide production})\\ &\quad \times 0.9\,(\text{efficiency of CCS at removing carbon dioxide from exhaust})\\ &\quad \times 3.4\,(\text{total cost of coal externalities}))\\ &= 1.928\,\text{p/kWh benefit due to CCS } CO_2 \text{ capture}.\end{aligned}$$

Therefore, 3.4−1.928 = 1.47 p/kWh.

5.1.8. *Externalities associated with diesel generation to be employed in Massawa*

ExternE presents external costs for the use of oil in the UK of 3–5€ cent/kWh. For the purposes of this research, the external cost associated with electricity generation via diesel to power the RO plants at Massawa will be taken as the lower end of the range at 2.5 p/kWh.

5.1.8.1. Energy security. The International Center for Technology Assessment (CTA) [23] presents a case for military and local storage costs in the US.

It makes the point that an indeterminate portion of the US, and other countries, defence budgets are concerned with protecting oil supplies by maintaining regional stability in the countries that produce oil. The estimated external costs associated with US military expenditure to protect the world's petroleum supplies range from \$47.6 billion to\$113.1 billion (£30.27 billion and £707,905 billion).

For the purposes of this paper, the cost of security for the fuel used to run the diesel generator in Massawa, is at the lower end of the range of the estimated security costs, presented by the CTA, at 2.4 p/l.

So, the total externalities due to use of diesel powered generation at Massawa, is 2.5 p/kWh of energy produced and 2.4 p/l of diesel fuel used.

5.1.9. *Costs associated with conventional power scenarios*

Based on the information above, the following sections provide detail of the costs used to model conventional power scenarios with externalities. It is noteworthy that the external costs used are the most

Table 8
External costs associated with power production using diesel generators at Massawa

	Total without externalities (£ ×10^6)	Additional cost due to externalities at £0.025/kWh of energy produced + £0.024/l of diesel fuel consumed over 25 years (£ ×10^6)	Total cost with externalities (£ ×10^6)
No BSR	231.7	102.4	**334**
PW	204.8	44.4	**249**
PX	171.1	33.6	**205**

conservative costs available from the information available.

5.1.9.1. Massawa. The costs associated with the externalities of power production at Massawa using diesel generators over the 25-year life of the installation are shown above in Table 8 for each of the RO plant types being modelled.

5.1.9.2. Newhaven. The costs associated with the externalities of power production at Newhaven using coal fired -plant with CCS over the 25-year life of the installation are shown below at Table 9 for each of the RO plant types being modelled.

5.1.10. Differences due to externalities at each site

The difference in externality cost between the Massawa (diesel powered) and Newhaven (Coal fired plant with CCS powered) scenarios can be seen above in Table 8 and below in Table 9. The externalities at Newhaven only increase the life cycle costs by four percent at the most, but the Massawa scenario costs increase significantly, almost half and a quarter, for the No BSR and BSR scenarios, respectively.

5.1.10.1. Amount of power required at each site. The feedwater at Newhaven is cooler than at Massawa, which means that more energy is required by the RO plants to make the equivalent amount of water as is shown below in Table 10.

When the increase in power required to produce water at Newhaven (between 31 and 40%) is taken into account, it is likely that using a coal- fired plant with CCS would be cheaper if applied at Massawa.

Table 9
External costs associated with power production using CCS at Newhaven

	Total without externalities (£ ×10^6)	Additional cost due to externalities at £0.0147/kWh over 25 years (£ ×10^6)	Total cost with externalities (£ ×10^6)
No BSR	211.7	8.98	**221**
PW	194.0	3.64	**198**
PX	164.1	2.89	**167**

Table 10
Power used to produce water at Massawa and Newhaven

	Annual power used at Massawa (kWh)	Annual power used at Newhaven (kWh)	Percentage increase in power use at Newhaven (%)
No BSR	1.8×10^7	2.5×10^7	40
Pelton Wheel BSR	7.6×10^6	10×10^6	31
Pressure Exchanger BSR	5.8×10^6	7.9×10^6	38

Table 11
Technically competent and most financially viable scenarios at Massawa when externalities are applied

Stage	Type of RO plant	Primary power (MW)	Secondary power	Secondary power (MW)	Hydrogen fuel	Ratio of renewable scenario cost against conventional	Ratio against conventional with externalities	Percentage difference (%)
1	No BSR	37.2	None	0	No	1.46	1.01	30.82
2	Pelton Wheel	21.8	None	0	No	1.694	1.392	17.82
	Pressure Exchanger	17.4	None	0	No	1.643	1.373	16.43
3	**No BSR**	**17.37**	**Wind**	**9.93**	**No**	**1.227**	**0.85**	**30.73**
	Pelton Wheel	3.69	Wind	14.68	No	1.353	1.112	17.81
	Pressure Exchanger	2.98	Wind	12.41	No	1.423	1.19	16.37
	No BSR	15.82	Wave	22.14	No	1.289	0.894	30.64
	Pelton Wheel	4	Wave	12.53	No	1.286	1.057	17.81
	Pressure Exchanger	2.98	Wave	12.15	No	1.273	1.064	16.42
4	No BSR	33.16	None	0	Yes	1.475	1.023	30.64
	Pelton Wheel	21.82	None	0	Yes	1.44	1.183	17.85
	Pressure Exchanger	17.39	None	0	Yes	1.408	1.176	16.48
	No BSR	9.69	Wave	19.73	Yes	1.316	0.913	30.62
	Pelton Wheel	3.41	Wave	10.68	Yes	1.253	1.0303	17.77
	Pressure Exchanger	2.67	Wave	8.14	Yes	1.237	1.033	16.49
	No BSR	13.45	Wind	15.38	Yes	1.317	0.913	30.68
	Pelton Wheel	7.22	Wind	7.43	Yes	1.257	1.033	17.82
	Pressure Exchanger	2.736	Wind	4.69	Yes	1.284	1.073	16.43

5.2. Results

Shown above in Table 11 and below in Table 12 are the results for the scenarios when externalities are applied at Massawa and Newhaven, respectively.

Scenarios that have become financially viable, (are cheaper that the conventionally powered equivalent), due to the application of externalities have a ratio of less than 1.

5.2.1. Conclusion

5.2.1.1. At Massawa. As can be seen from Table 11 above, four of the five No BSR scenarios have become financially viable due to the application of externalities, which accounted for a difference of more than 30% against the scenarios without externalities. The most financially attractive scenario used a combination of solar and wind power and is highlighted in bold.

5.2.1.2. At Newhaven. As can be seen from Table 12 below, the addition of externalities has not made any of the scenarios at Newhaven financially viable, due to the limited external costs associated with CCS, but it has given a slight improvement to their prospects with the most financially attractive scenario (Pressure Exchanger BSR RO plant using tidal current combined with wave power highlighted in bold text) now being less than 17% from financial viability.

Table 12
Technically competent and most financially attractive scenarios at Newhaven when externalities are applied

Stage	Type of RO plant	Primary power (MW)	Secondary power	Secondary power (MW)	Hydrogen storage	Ratio of renewable scenario cost against conventional	Ratio against conventional with externalities	Percentage difference (%)
1	No BSR	135.3	None	0	No	2.969	2.848	4.08
2	Pelton Wheel	66.5	None	0	No	2.525	2.479	1.82
	Pressure Exchanger	54.38	None	0	No	2.469	2.426	1.74
3	No BSR	20.5	Wind	29.48	No	1.527	1.465	4.06
	Pelton Wheel	5.59	Wind	14.12	No	1.38	1.355	1.81
	Pressure Exchanger	4.28	Wind	13.72	No	1.358	1.334	1.78
	No BSR	20.5	Wave	19.62	No	1.443	1.384	4.09
	Pelton Wheel	5.59	Wave	7.63	No	1.196	1.174	1.84
	Pressure Exchanger	**4.28**	**Wave**	**6.33**	**No**	**1.188**	**1.168**	**1.68**
4	No BSR	122.5	None	0	Yes	3.118	2.991	4.07
	Pelton Wheel	54.38	None	0	Yes	2.474	2.429	1.82
	Pressure Exchanger	45.37	None	0	Yes	2.371	2.33	1.73
	No BSR	15.84	Wave	15.41	Yes	1.607	1.542	4.043
	Pelton Wheel	4.88	Wave	6.67	Yes	1.26	1.237	1.83
	Pressure Exchanger	4.28	Wave	4.75	Yes	1.253	1.232	1.68
	No BSR	14.67	Wind	21.09	Yes	1.651	1.577	4.48
	Pelton Wheel	6.11	Wind	8.24	Yes	1.362	1.337	1.84
	Pressure Exchanger	4.06	Wind	7.3	Yes	1.303	1.281	1.69

Table 13
Most financially favourable option at Massawa

Type of RO plant	Renewable power sources	Total power installed (kW)	Ratio of cost of renewable to conventional energy scenario	Ratio of cost of renewable to conventional energy scenario taking externalities into account
No BSR	Solar and wind	27,301	1.227	0.85

Table 14
Most financially favourable option at Newhaven

Type of RO plant	Renewable power sources	Total power installed (kW)	Ratio of cost of renewable to conventional energy scenario	Ratio of cost of renewable to conventional energy scenario taking externalities into account.
Pressure Exchanger	Tidal current and wave	10,603	1.19	1.17

6. Conclusion

The objective of this research was to assess the viability of renewable energy to completely displace a conventional power source, and provide a fundamental and significant human need.

To make this assessment, this paper has modelled various scenarios at Massawa in Eritrea and Newhaven in South East England, with a view to addressing the water needs of 50,000 people using various RO plant types, such as:

- A simple plant with No BSR.
- A BSR Plant with a Pelton Wheel, to re-use captured energy in the brine stream.
- A BSR Plant with Pressure Exchanger mechanism to re-use captured energy in the brine stream.

Combinations of renewable energy were also investigated, as follows:

- At Massawa
  - Solar energy.
  - Solar and wind energy.
  - Solar and wave energy.
- Newhaven
  - Tidal current energy.
  - Tidal current and wind energy.
  - Tidal current and wave energy.
- Hydrogen fuel.

The research has demonstrated that a significant and fundamental human need can be addressed by using renewable energy.

All the combinations of renewable energy sources modelled were able to meet the water requirements of 50,000 people at each site.

With respect to the cost associated with meeting such a need, although the scenarios that employed energy storage were more economic, with respect to installed energy capacity, in achieving the required water output, the most financially viable scenario was at Massawa, using solar and wind power and a simple No BSR RO plant.

A relatively simple hybrid renewable energy plant such as this:

- Minimises the difficulties associated with the operation of very complex machinery required to implement many of the other modelled scenarios, and;
- Improves the prospects for Massawa to have security over its water supply.

The financial attractiveness of the Massawa wind and solar hybrid scenario is due to:

- The relatively cheap costs associated with onshore wind power, even in the relatively poor wind climate modelled;
- The high current costs associated with hydrogen generation and re-use;
- That the ability to scale up the RO plant allowed over production of water, using energy that would have otherwise been wasted, and storage in a reservoir effectively storing wasted energy as water relatively cheaply in comparison with hydrogen.
- The high cost of externalities associated with diesel fuel.

A simple précis of the most financially viable scenarios is presented below for Massawa and Newhaven, at Tables 13 and 14, respectively, showing:

- The type of RO plant;
- The renewable power source employed by the scenario;
- The total renewable power capacity installed for the scenario;
- The "Ratio" of cost of the renewable powered scenario compared with the conventionally powered equivalent, over 25 years. (Less than "1" is taken as financially viable), and;
- The 'Ratio" of cost of the renewable powered scenario in relation to the conventionally powered equivalent over 25 years, when the externalities associated with conventional energy was taken into account. Less than "1" is taken as being financially viable.

It was noteworthy that:

- There is a significant difference in the cost of scenarios, due to the quantity, and combination of energy sources used;
- None of the scenarios modelled was initially financially viable, and;
- The No BSR RO plant with solar and wind energy (and another three of the No BSR RO plant) scenarios at Massawa only become financially viable when the externalities associated with the use of diesel fuel were applied.

Although, to be financially viable in the "real world", (to realise the cost benefit of these externalities), would require the support of a scheme such as the "Clean Development Mechanism", which acknowledges the cost associated with the externalities of conventional power use.

None of the scenarios modelled at Newhaven, when compared with the modelled coal fired -plant with CCS plant, was financially viable over the life of the facility. The most financially favourable Newhaven scenario (shown above in Table 14) was 19 and 17% too expensive without and with externalities, respectively.

Overall conclusions are that:

- It is possible to desalinate water for human consumption at Massawa and Newhaven, using renewable energy.
- This is financially viable at Massawa when the externalities of diesel fuel are considered;
- The costs of using renewable energy at Newhaven are (at best) 17% greater than when using conventional energy.
- There is significant scope to improve the scenarios, to make many of them more financially viable than identified within this research.

References

[1] World Health Organization, Guidelines for drinking-water quality, fourth ed., ISBN 978 92 4 154815 1, 2011. Available from: http://www.who.int/water_sanitation_health/publications/2011/dwq_chapters/en/index.html.

[2] M. Thomson, M. Miranda, J. Gwillim, A. Rowbottom, I. Draisey, Batteryless Reverse Osmosis Desalination System, DTI Publication URN 01/1121, Detail of water composition provided at Appendix C, 2001. Available from: http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file16527.pdf.

[3] M. Thomson, Doctoral Thesis, Reverse-Osmosis Desalination of Seawater Powered by Photovoltaics without Batteries, Loughborough University, 30th June, 2003, pp. 110–111. Available from: http://www-staff.lboro.ac.uk/~elmt/Murray%20Thomson%20Thesis.pdf.

[4] Centre for Environment, Fisheries & Aquaculture Science (Cefas) website. Available from: http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/sea-temperature-and-salinity-trends/presentation-of-results/station-20-eastbourne.aspx?RedirectMessage=true.

[5] The US Department of Energy (DOE) tip sheet (DOE/GO-102007-2230, Pumping systems Tip Sheet 2 'control strategies for centrifugal pumps with variable flowrate requirements'), May 2007. Available from: http://www1.eere.energy.gov/industry/bestpractices/pdfs/38949.pdf.

[6] M. Thomson, Doctoral Thesis, Reverse-Osmosis Desalination of Seawater Powered by Photovoltaics without Batteries, Loughborough University, 30th June, 2003, Monthly averages taken from page, p. 95. Available from: http://www-staff.lboro.ac.uk/~elmt/Murray%20Thomson%20Thesis.pdf.

[7] Sharp 235 W Solar Panel, Monocrystalline, Clear, NU-U235F1 data sheet. Available from: http://www.pvpower.com/pdf/datasheets/sharp/pv%20modules/235spec.pdf.

[8] L Olga, V. Sallangos, Operating experience of the Dhekelia seawater desalination plant using an innovative energy recovery system, Desalination 173 (2005) 91–102. Available from: http://159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf.

[9] NOABL Wind Map. Available from: http://www.rensmart.com/Weather/BERR, Newhaven data based on the following coordinates. 50.78076029964647 Lat: 0.0473785400390625 long.

[10] Weatherbase website. Available from: http://www.weatherbase.com/weather/weather.php3?s=32036.

[11] P. Meisen, Ocean Energy Technologies for Renewable Energy Generation, Global Energy Network Institute (GENI), August 2009. Available from: http://www.geni.org/globalenergy/research/ocean-energy-technologies/Ocean%20Energy%20Technologies.pdf.

[12] J.W.C. Boyle, Design, Construction and repair of Potable Water Reservoirs, April 2008. Available from: http://bcwwa.org/resourcelibrary/BOYLE_~1.PDF.

[13] G. Schellekens et al., 100% renewable electricity—A roadmap to 2050 for Europe and North Africa, 2010. Available from: http://www.pwc.co.uk/assets/pdf/100-percent-renewable-electricity.pdf.

[14] Electric Power Research Institute Inc. (EPRI), System Level Design, Performance, Cost and Economic Assessment—San Francisco Tidal In-Stream Power Plant, 10 June, 2006. Available from: http://oceanenergy.epri.com/attachments/streamenergy/reports/006_CA_06-10_-06.pdf.

[15] Parsons Brinckerhoff, Powering the Future, Full Report—Mapping our low-carbon path to 2050, December 2009. Available from: http://www.pbworld.com/pdfs/powering_the_future/pb_ptf_full_report.pdf.

[16] Based on e-mail correspondence on '14 Jan 2011' with Paul Wilson of Parsons Brinckerhoff author of 'Powering the Nation'. Available from: http://www.pbpoweringthefuture.com/.

[17] E.I. Zoulias, N. Lymberopoulos, Hydrogen-based autonomous power systems: techno-economic analysis of the integration of Hydrogen in Autonomous Power Systems. Available from: http://www.springer.com/engineering/energy+technology/book/978-1-84800-246-3.

[18] M. Hirscher, Handbook of Hydrogen Storage—New Materials for Future Energy Storage, WILEY-VCH, 2010, ISBN 978-3-527-32273-2.

[19] F.M. Hordeski, Hydrogen and Fuel Cells: Advances in Transportation and Power, Fairmont Press, 2009, ISBN 0-88173-562-0.

[20] A.M. Shipley, R.N. Elliot, Stationary fuel cells—future promise, current hype, Report IE041, American Council for an Energy-Efficient Economy, 2004.

[21] Final report from ExternE 'European Commission EUR 20198—External Costs Research results on socio-environmental damages due to electricity and transport', ISBN 92-894-3353-1, 2003. Available from: http://ec.europa.eu/research/energy/pdf/externe_en.pdf.

[22] 'Cleaner Coal'. Postnote. Parliamentary Office of Science and Technology. Number 253, December 2005. Available from: http://www.parliament.uk/documents/post/postpn253.pdf.

[23] International Center for Technology Assessment (CTA), Gasoline Cost Externalities: Security and Protection services, An update to CTA's Real Price of Gasoline Report, Jan 25, 2005.