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# Seawater Greenhouse Development for Oman: Thermodynamic Modelling and Economic Analysis

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**November 2001**

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## Project 97-AS-005b



Edited and typeset by Edgerton Publishing Services, UK

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# ABSTRACT

The main objective of our study was to determine the influence of greenhouse-related parameters on a desalination process that combines fresh water production with the growth of crops in a greenhouse system. A thermodynamic model was used based on heat and mass balances. The thermodynamic and economic efficiencies of solar desalination systems were also briefly reviewed. While solar distillation plants have been around for over a century, the concept of using them in combination with the growth of crops in a greenhouse is new. With the Seawater Greenhouse, surface seawater trickles down a porous front wall evaporator through which air is drawn into the greenhouse. The saturated air passes through a condenser, which is cooled using cold deep seawater or cool seawater from the evaporators. Thermodynamic modelling has shown that the dimensions of the greenhouse had the greatest overall effect on the water production and energy consumption. Low power consumption went hand-in-hand with high efficiency. Total fresh water production for three internal climate scenarios was also calculated. The benefits of the development of the Seawater Greenhouse in arid regions such as the Arabian Gulf were discussed.

# ACKNOWLEDGEMENTS

This report covers the activities of the project 'Seawater Greenhouse Development for Oman: Thermodynamic Modelling and Economic Analysis.' It has been made possible through funding from the Middle East Desalination Centre (MEDRC).

Additional support has been provided by the Department for International Development (DFID) UK, Light Works Ltd, Sultan Qaboos University and the Rufford Foundation.

# EXECUTIVE SUMMARY

The Seawater Greenhouse combines horticulture with solar desalination. While the concept of solar distillation within a glazed enclosure dates back more than 100 years, the idea of combining it with the growth of crops in a controlled greenhouse environment is new.

## Objectives

This report presents an analysis of the predicted performance of the Seawater Greenhouse in Oman. The thermodynamic and economic efficiencies of solar desalination systems are also reviewed. The main objective of our study was to determine the influence of greenhouse-related parameters on a desalination process that combines fresh water production with the growth of crops in a greenhouse system. A thermodynamic model was used based on heat and mass balances. Simulation runs were carried out to achieve the following objectives:

- to evaluate the optimum configuration of the greenhouse;
- to evaluate the performance of three different versions of the greenhouse described as temperate, tropical and oasis;
- to conduct an optimization and sensitivity study.

## Literature review

### Multiple effect solar stills

Multiple-effect solar desalination systems are more productive than single effect systems due to the reuse of latent heat of condensation. The increase in efficiency, though, must be balanced against the increase in capital and operating costs. The efficiency of a multiple-effect solar still can be increased, for example, by inclining the glass cover surface towards the sun and installing grooves on the upper surface of the glass to hold and warm the saline water before it enters the still. The efficiency of the system can also be improved by running it in an upward-type mode. The addition of flat plate collectors and heat exchangers to transfer waste heat from local industry provides an additional way of enhancing the productivity.

### Humidification–dehumidification systems

Several pilot plants have been developed over the past four decades. One such plant employed solar absorbers to preheat the water before it was circulated through an evaporation chamber. Another system employed a solar pond to load the air with humidity followed by a dehumidification column to collect the fresh water. A closed air cycle humidification–dehumidification desalination process has also been used in combination with a flat-plate solar collector. An open-air open-water humidification–dehumidification greenhouse structure was developed for desalination and for crop growth. The Seawater Greenhouse uses seawater evaporators to cool and humidify the air. The greenhouse acts as a solar still while providing a controlled environment suited to the cultivation of crops.

## Economics

Lower operating costs in the form of alternative energy sources (e.g. waste heat or wind energy) have been found to be key factors in the economic viability of solar desalination systems. Solar still plants have a mean lifetime of about 20 years while the cost of fresh water produced by solar plants ranges from US \$0.52 $m^{-3}$ to US \$2.99 $m^{-3}$, depending on the plant and the cost analysis method. It is important to realize that maximum output does not mean that a solar still is the most economical.

# Seawater Greenhouse

The Seawater Greenhouse is one of the more novel and effective humidification–dehumidification systems that have been developed over the past decade. The Seawater Greenhouse uses sunlight, seawater and the atmosphere to produce fresh water and cool air, creating more temperate conditions for the cultivation of crops. The process recreates the natural hydrological cycle within a controlled environment. Surface seawater trickles down the front wall evaporator, through which air is drawn into the greenhouse. Dust, salt spray, pollen and insects are trapped and filtered out leaving the air pure, humidified and cool. Sunlight is selectively filtered by the roof elements to remove radiation that does not contribute to photosynthesis. This helps to keep the greenhouse cool while allowing the crops to grow in high light conditions. Air passes through a second seawater evaporator and is further humidified to saturation point. Saturated air passes through the condenser, which is cooled using cold deep seawater. Pure distilled water condenses and is piped to storage. Fans draw the air through the greenhouse and into a shaded house area.

## Thermodynamic model

A software program developed by Light Works Limited, was used to model the Seawater Greenhouse system. The computer program consists of several modules: seapipe, airflow, evaporator 1, roof, planting area, evaporator 2, condenser (air/water heat exchanger). The model is based on experience with the Tenerife Greenhouse. It takes into account several well-understood physical processes:

- evaporative cooling;
- solar heating;
- heat loss from the building;
- transpiration based on the Penman equation;
- heat transfer in a tube and fin heat exchanger;
- ventilation driven by a fan with assistance from the wind.

Each process is described within a block of the model. The blocks are linked together in such a way that the mass and energy flows in and out of the blocks sum to zero, in accordance with the first law of thermodynamics. The software used to implement the model is MATLAB and Simulink. Weather data provides the input to the model. The model allows parameters to be adjusted to meet a particular goal of internal climate, water production or energy use.

# Simulation studies

## Optimal configuration of the greenhouse

Thermodynamic modelling has shown that the dimensions of the greenhouse had the greatest overall effect on the water production and energy consumption. Low power consumption went hand-in-hand with high efficiency. A wide shallow greenhouse, 200 m wide by 50 m deep gave 125 $m^3$ per day of fresh water. This was greater than a factor of two compared to the worst-case scenario with the same overall area (50 m wide by 200 m deep), which gave 58 $m^3$ per day. Low power consumption went hand-in-hand with high efficiency. The wide shallow greenhouse consumed 1.16 kWh $m^{-3}$, while the narrow deep structure consumed 5.02 kWh $m^{-3}$.

## Performance of different versions of the Seawater Greenhouse

Total fresh water production for three different versions was also calculated. One year's detailed meteorological data from Seeb Airport, Muscat was entered into the model to test the performance sensitivity for various designs. The model results predict that the Seawater Greenhouse will perform efficiently throughout the year, but with measurable variations in performance between the alternative versions. The water production rate and energy efficiency results from the simulations using optimized and constant values for fan and pump speeds were as as shown in the following table.

**Annual water production and energy efficiency for three greenhouse versions**

| | Total fresh water produced ($m^3$ per annum per hectare) | Power consumption (kWh $m^{-3}$) |
|---|---|---|
| **Temperate** | 20,370 | 1.9 |
| **Tropical** | 11,574 | 1.6 |
| **Oasis** | 23,529 | 2.3 |

## Optimization and sensitivity study

The next table shows the performance at the optimum settings. Water productivity can be improved but with greater energy consumption, and efficiency can be improved but with a small reduction in water output.

**Annual water production and energy efficiency for three greenhouse versions with varying pump and fan speeds**

| Model | Orientation (°) | Fan gain | Pump trigger | Product water ($m^3$) per annum | Product water (per annum per hectare) | kWh used | Power consumption kWh $m^{-3}$ |
|---|---|---|---|---|---|---|---|
| **Temperate** | 50 | 0.14 | 0.2 | 2,000 | 18,519 | 2,500 | 1.25 |
| **Tropical** | 50 | 0.14 | 0.2 | 1,800 | 16,667 | 1,760 | 0.98 |
| **Oasis** | 50 | 0.14 | 0.2 | 3,200 | 20,915 | 4,500 | 1.41 |

# Cost comparison

From the results of the optimization study, values of litres per square metre (L $m^{-2}$) of floor space were calculated for different versions of the Seawater Greenhouse. Using the cost of the greenhouse structure and components, together with the value for the external area that could be supported by the surplus water, the cost effectiveness is shown in the table below.

**Summary of cost and performance for three greenhouse versions**

| | Temperate model | Tropical model | Oasis model |
|---|---|---|---|
| **Area, water production and cost** | | | |
| **Greenhouse length (m)** | 60 | 60 | 85 |
| **Greenhouse area ($m^2$)** | 1,080 | 1,080 | 1,530 |
| **External irrigated area under shade netting ($m^2$)** | 1,030 | 590 | 1,690 |
| | | | |
| **Total cultivated area ($m^2$)** | 2,110 | 1,670 | 3,220 |
| | | | |
| **Average water production ($m^3$ day–$^1$)** | 6.03 | 3.42 | 9.86 |
| | | | |
| **Capital cost (£)** | 34,379 | 34,379 | 43,902 |
| **Capital cost per hectare (£)** | 318,326 | 318,326 | 286,939 |
| | | | |
| **Annual crop sales, costs and profit** | | | |
| **Total annual income (£)** | 22,330 | 19,250 | 33,250 |

# Significance

The benefits to Oman of the Seawater Greenhouse development on a commercial scale can be summarized as:

- the opportunity to develop a high-value agricultural sector that is sustainable in the long term and does not depend on rainfall or groundwater;
- new market options – for import substitution and export development;
- additional water supplies for other purposes;
- restoration of land that has become toxic with salinity;
- opportunities to develop environmental projects such as the clean-up, reuse and disposal of production water in the oil industry.